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STRUCTURAL DYNAMICS AND ATTITUDE CONTROL STUDY OF EARLY MANNED CAPABILITY SPACE STATION CONFIGURATIONS

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BY

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ON THE COVER PAGE THE NAME "BEN K. WADA" SHOULD BE ADDED AS AN AUTHOR OF THE REPORT.

ON BIBLIOGRAPHIC PAGE, ITEM 15, ADD
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Contents

Nomenclature

ACS	Attitude Control System
CETF	Critical Evaluation Task Force
CMG	Control Moment Gyro
ESA	European Space Agency
EVA	Extra-Vehicular Activity
HAB Module	Habitation Module
JEM	Japanese Experiment Module
LAB Module	Laboratory Module
LOG Module	Logistics Module
MSC	Mobile Servicing Center
PV	Photo-Voltaic Module
RCS	Reaction Control System
SD	Solar Dynamic Power Module

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1.0 Introduction

The space station Critical Evaluation Task Force (CETF) which met at the Langley Research Center August 23 through September 12, 1986, identified alternate options to the then-baselined Initial Operating Capacity (IOC) space station and its assembly sequence. Critical evaluation factors included the amount of EVA required for assembly and maintenance of the station, launch capacity of the shuttle fleet assembly sequence of the baseline configuration, any resultant impact of alternate options to the utilization of the station and on international partners, and overall technical performance and integrity of the station.

For the analysis described herein, five representative configurations were selected from the various alternatives presented to the CETF, and were examined to determine their vibration and attitude control characteristics. These five represented a version of the currently baselined dual keel as well as four intermediate stages of assembly. Thus, the analysis shows the changes that are likely to occur in the characteristics of the system as the station progresses from a simple boom structure to a mature dual keel.

The purpose of this report is to describe the models which were developed and the results of the vibration and attitude control analyses.

2.0 Selected Configurations

Because of the time constraints imposed by the CETF, completion of this study required that the configurations to be modelled and analyzed be selected prior to the task force finalizing the details of its recommended options (see reference 1)*. The configurations presented herein, though not identical to the specific option recommended by the CETF, are sufficiently representative for the purpose of vibration and attitude control analysis. Where a specific modelling decision was required, it was done to produce a conservative result. The configurations studied in this report are summarized below.

Configuration A (Boom with Photo-Voltaic power):

> The major components of this configuration appear in table 1 and can be seen on figure 1. It was evaluated to determine its vibration modes with and without the shuttle attached. When the structure is attached to the orbiter payload bay, the situation is representative of the final stages of the second assembly flight as described in reference 1.
>
> The primary concern of this analysis relates to orbiter payload requirements and orbiter attitude control with a large truss structure attached (See Ref. 2 for a similar analysis).

* The CETF produced no referencable documentation. Most of the CETF results have been baselined by the space station program and incorporated into the apprpopiate places in the documentation tree. Reference a is one example of this process.

Configuration B (Boom with PV and U.S. Modules):

The components of this configuration are shown in table 1 and the complete configuration appears on figure 2. It corresponds approximately to the configuration that would be achieved after the seventh flight of the assembly sequence recommended by the CETF.

Configuration C (Configuration B with MSC and Solar Dynamic Power):

Configuration C contains the components shown in table 1, and appears as shown on figure 3. It corresponds approximately to the configuration which results from nine flights of the recommended CETF assembly sequence.

Configuration D (Configuration C with ESA and JEM Modules):

This configuration is identical to configuration C except for the addition of the international modules. Table 1 and figure 4 show its major components. Configuration D corresponds approximately to the result of eleven flights of the recommended CETF assembly sequence.

Configuration E (Reference Dual Keel) :

Configuration E includes all the major components in table 1 and is shown on figure 5. It closely resembles the dual keel configuration which served as the initial reference for the CETF activity, and is also highly representative of the final dual keel configuration which would result from sixteen flights of the assembly sequence recommended by the CETF. However, configuration E, like the initial reference configuration, includes a back porch, whereas the final CETF dual keel did not. While the presence of a back porch produces a stiffer structure, the overall characteristics are similar enough to those of the final CETF configuration that the results are valid and meaningful.

Table 1 : Major Components of each Configuration

Configuration (Comp. Wt.)	A	B	C	D	E
PV Module (10351 lbf)	X	X	X	X	X
4 RCS Pods (8420 lbf)	X	X	X	X	X
Radiator (4940 lbf)	X	X	X	X	X
Module Cluster (12900 lbf)		X	X	X	X
SAAX0251 (939 lbf)		X	X	X	X
TDMX2421 (4020 lbf)		X	X	X	X
MSC (10800 lbf)			X	X	X
Solar Dynamic Collectors (23350 lbf)			X	X	X
ESA Module (43000 lbf)				X	X
JEM Module (66150 lbf)				X	X
Back Porch (1373 lbf)					X
Dual Keels					X

Notes : 1. Configurations A and B have only one Radiator, while C, D, and E have two.

2. The Module Cluster includes the US LAB and HAB modules, fore and aft nodes, 2 tunnels, a hyperbaric chamber, the LOG module, and one Cupola.

Figure 1 : Configuration A

Boom with Photo-Voltaic (PV)

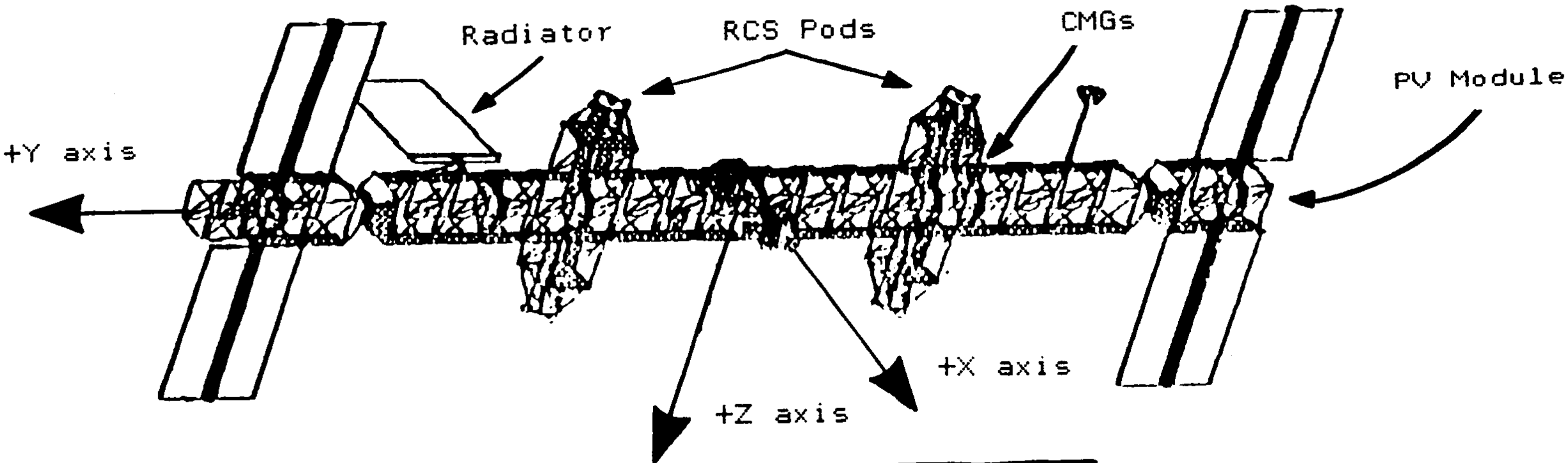
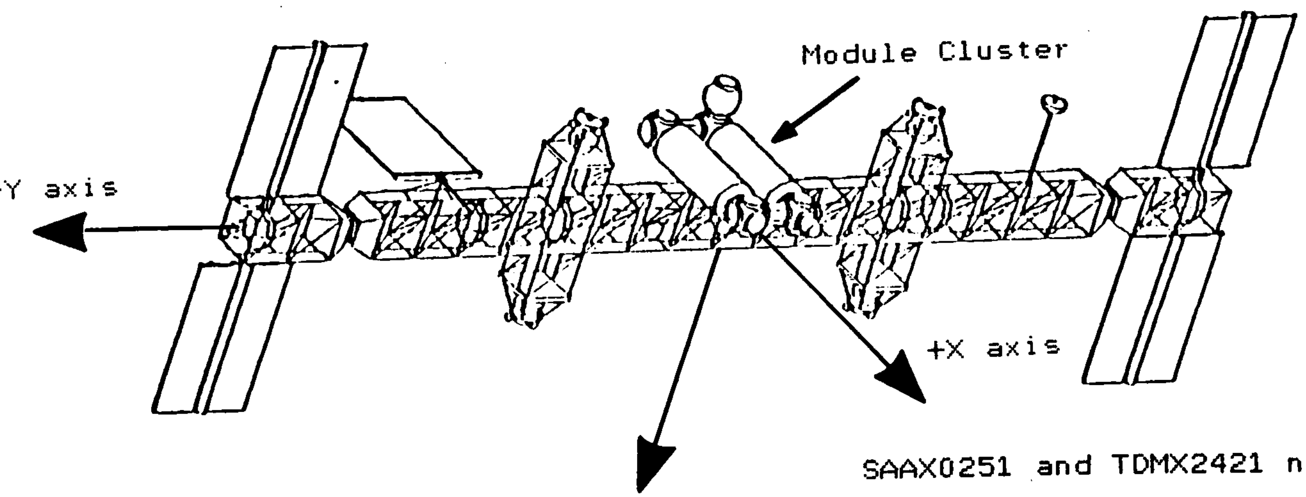


Figure 2 : Configuration B

Boom with PV and U.S. Modules



SAAX0251 and TDMX2421 not shown

Figure 3 : Configuration C

Boom with PV, Solar Dynamic & U.S. Modules

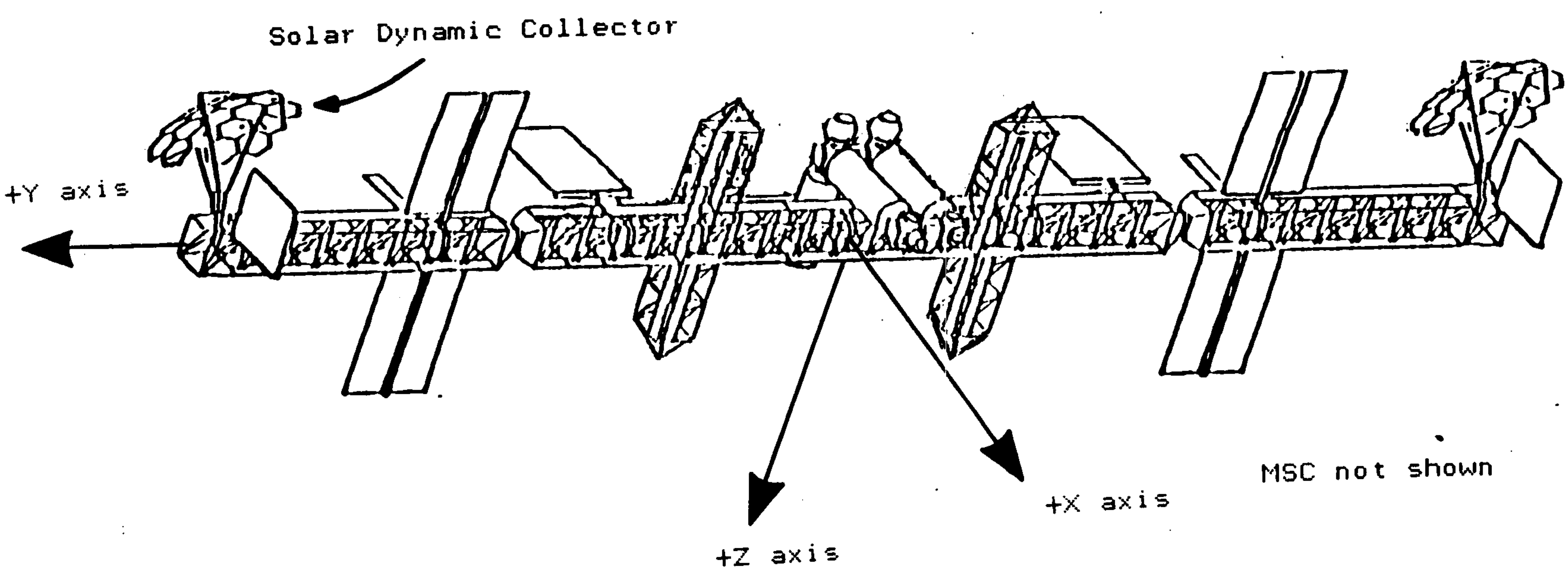


Figure 4 : Configuration D

Boom with PV, Solar Dynamic, U.S. & Inter. Modules

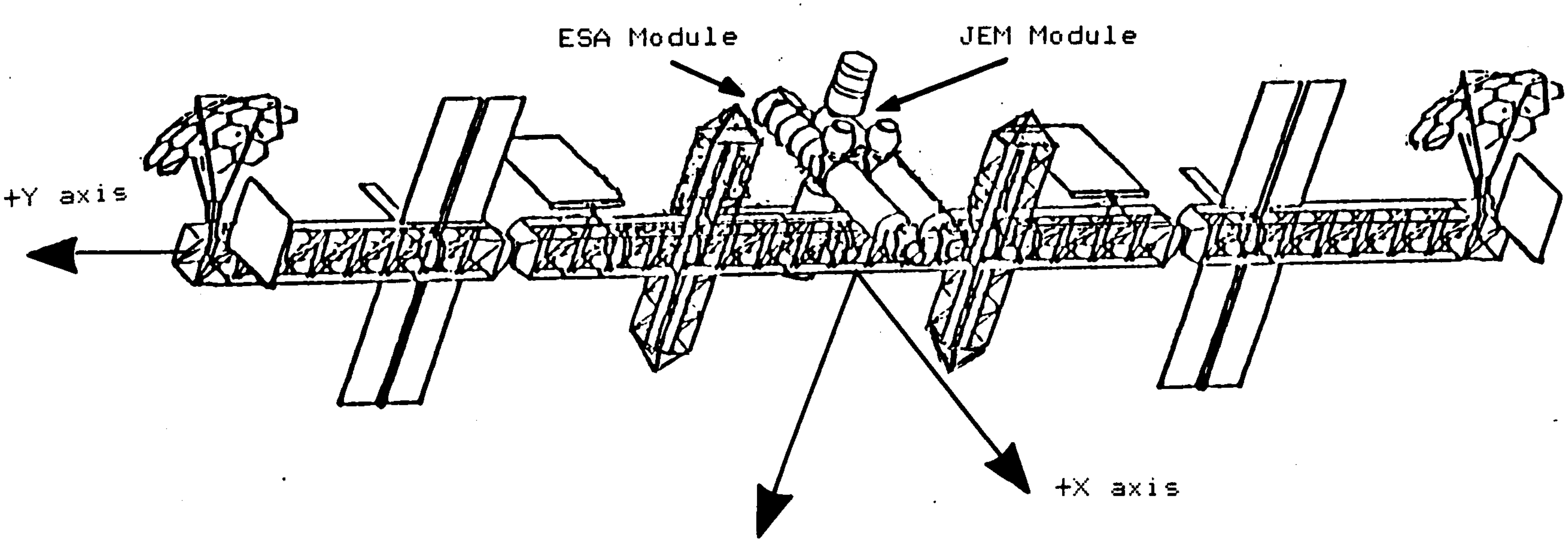
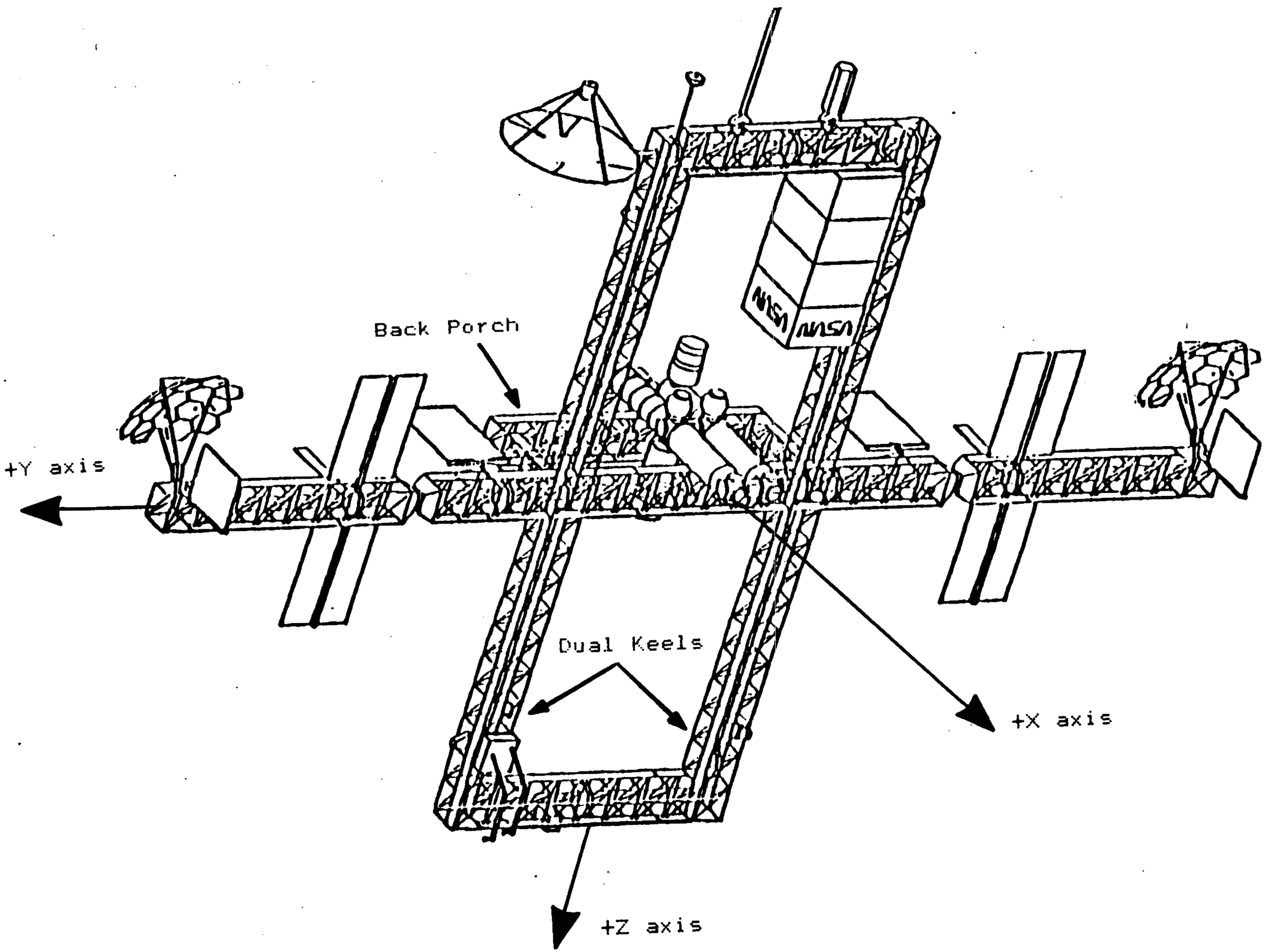


Figure 5 : Configuration E

Dual Keel



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3.0 Method of Analysis

The five CETF configurations described above were analyzed in two steps; the natural modes and frequencies of each configuration were determined, and the results were used to evaluate the relative controllability characteristics of configurations B, C, D, and E. The following sections describe the finite element models that were developed, as well as the specific approaches followed to determine the vibration and attitude control characteristics of each configuration.

3.1 Finite Element Models

Models of each of the five configurations were developed using the SUPERTAB finite element modelling package, and the vibration analysis was done with the MSC/NASTRAN finite element analysis program. Each model consisted of an appropriate number of truss bays, with truss members modelled as rods (axial stiffness only), and connected by pin joints which were modelled as lumped masses. The physical and material properties of the truss members represented the most up to date values available for actual proposed space station truss members.

Most of the payloads on each configuration were modeled as mass and inertia only and were put in the appropriate position on the structure as indicated by the preliminary information from the CETF activity. However, the US HAB and LAB modules, the international modules, the radiators, and the photo-voltaic booms were all modelled as beams with bending, torsional and axial stiffnesses accurately represented.

Because of the requirements of the CETF to re-evaluate previous decisions, it was necessary to determine the dynamic characteristics of the five configurations with both 5 meter and 9 foot truss bays (see references 3 and 4). However, because of the time constraints it was not possible to develop 9 foot versions of each model. Instead, in an effort to minimize the modelling effort and still produce meaningful results to support the CETF decision making process, each 5 meter model was modified to simulate the effective stiffness of an identical 9 foot model. This was accomplished by simply reducing the modulus of elasticity for each truss member by a reduction factor. The reduction factor for this process was calculated as follows:

5 meters = 16.404 ft

Reduction Factor = (9 ft / 16.404 ft)**2 = 0.301

Thus, by multiplying the modulus of each truss member by 0.301, the system would exhibit the approximate bending and torsional stiffness (though not the axial stiffness) of a 9 foot bay truss.

3.2 Vibration Characteristics

The aim of this analysis was to determine the changes in the natural vibration characteristics of the space station as it grows from a single truss boom to a complete dual keel configuration. It was also deemed necessary to re-evaluate the differences between 5 meter and 9 foot truss bays. Thus, modes and frequencies were obtained for each of five configurations with 5 meter bays, as well as with the equivalent stiffness of 9 foot bays as described above. In addition, modes and frequencies were calculated for configuration A with the shuttle attached to one end of the boom, in order to determine the characteristics of the system as the initial truss assembly procedure nears completion. In this case, the shuttle was modelled as mass and inertia only, and was rigidly attached to the end of the boom.

3.3 Attitude Control Characteristics

Analysis of attitude control followed the approach outlined in NASA TM 87679 (Ref.4). Configurations B through E were evaluated for controllability about each of their three axes. The attitude control loop is shown schematically in the block diagram of figure 6 (Fig. 21 of Ref. 4). As in Ref. 4, the dynamic response characteristics of the sensor package and the CMG's are not considered. Hence, the sensed attitude angles and rates are exact, and the control moments produced by the CMG's are exactly those commanded. The controller used here is the compensated proportional plus differential (PD) controller of Ref. 4. The form of this controller is defined by the transfer function

$$\frac{M_{ye}(s)}{\theta_{ye}(s)} = \frac{K's + K}{s/p + 1} .$$

For the purposes of this study, the sensor was assumed to be co-located with the Control Moment Gyro (CMG).

The reader is referred to the section ATTITUDE CONTROL SYSTEM STUDY of reference 4 for a complete description of the attitude control analysis methodology. The subsection "Control Law Compensation" presents the compensated PD controller which was adapted for this study.

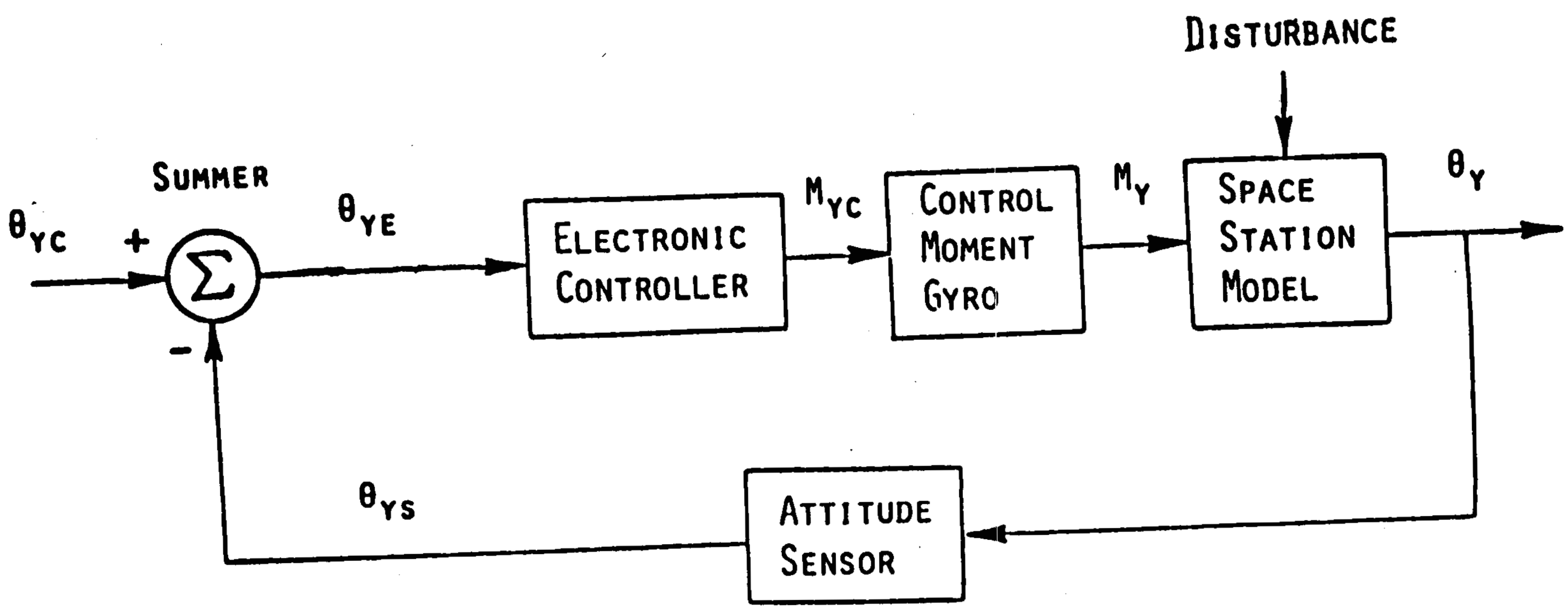
This controller was designed to give a bandwidth of 0.01Hz and 27.5% damping ratio. This was transfered to the present models by adjusting the gains of the controller of reference 4 in proportion to the moments of inertia of each configuration. Values of the K and K', the proportional and differential gains, and of p, the "break frequency" of the first-order lag, used in this study are given in table 2. It should be noted that for each configuration, identical gain values were used for both the 9 foot and 5 meter bay sizes. This was done because the method of simulating the stiffness of the 9 foot bay size did not alter the mass properties (see section 3.1). Modal damping of 0.5 percent was assumed for the space station truss structure.

Bode' plots constructed for each axis of each model were used to assess the relative stability characteristics of each configuration. The Bode' plots were constructed for the controller acting on the x-, y-, and z-axes of the space station, one at a time. No attempt was made to assess the effects of cross-axis coupling which may occur when the controllers act simultaneously. Similarly, no attempt was made to tune the controller of reference 4 to the present structures except for the proportional shift in gains already mentioned.

Table 2 : Controller Parameter Values

$p = 0.0582$

	Feedback Gains Used in each Configuration		
Configuration	Axis	K	K'
B	X Y Z	313,000. 33,900. 320,000.	12,910,000. 1,398,000. 13,200,000.
C	X Y Z	1,138,000. 45,900. 1,136,000.	46,900,000. 1,894,000. 46,800,000.
D	X Y Z	1,147,000. 135,300. 1,225,000.	47,300,000. 5,580,000. 50,500,000.
E	X Y Z	1,922,000. 915,000. 1,252,000.	79,300,000. 37,700,000. 51,600,000.



θ_Y - SPACE STATION ATTITUDE

θ_{YS} - SENSED ATTITUDE

θ_{YC} - COMMANDED ATTITUDE

θ_{YE} - ATTITUDE ERROR

M_Y - CONTROL MOMENT

M_{YC} - COMMANDED CONTROL MOMENT

Figure 6 : Block Diagram of Attitude Control System

4.0 Discussion of Results

4.1 Vibration Characteristics

Table 3 shows the frequency of the first bending mode of the space station boom for each of the assembly stages represented by configurations A - E. In each case, the first bending mode of the boom was the lowest true structural mode for the system, though in some instances there were various appendage modes (such as bending and torsion of the solar arrays) which appeared at lower frequencies. The results shown in table 3 provide a good summary of the effects of adding truss and payloads to the station, as well as the differences between 5 meter and 9 foot truss bays.

As expected, the addition of large masses such as the shuttle, solar dynamic collectors, and US and international modules to the structure, decreased the frequency significantly. It was only configuration E, the reference dual keel, which showed an increase in boom bending frequency from the previous configuration. Also as expected, the structures with 5 meter bays exhibited a significantly higher frequency than the structures with the equiv   alent stiffness of 9 foot bays.

Appendices A - E contain tables of mass properties, descriptions of various vibration modes, and plots of representative modes shapes for each of the five configurations.

4.2 Attitude Control Characteristics

The open loop gain -vs- frequency portion of the Bode' plots for configurations B through E are presented in appendices B through E respectively. Results are presented for both 9 foot and 5 meter truss bay sizes in figures 1a and 1b of each of these appendices. Although Bode' analyses were completed for each control axis of each configuration, only the X-axis results are presented because the gain margins for the X-axis controllers were consistently lower than for the other axes (see table 4). Minimum gain margins for the X-axis controllers were consistently associated with the first structural mode of each configuration.

All configurations and truss bay sizes exhibited positive gain margins. However, the 5 meter bay size structure consistently exhibited positive gain margins approximately 10 dB higher than the 9 foot bay size.

In summary, .01 bandwidth compensated proportional plus differential controllers exhibited stable performance on all axes of all truss bay sizes of all configurations. The 5 meter bay size structure is more attractive, however, because of its inherently higher stiffness and higher gain margins.

Table 3 : First Boom Bending Frequency for Each Configuration.

Configuration	1st Boom Bending Frequency (Hz) 5 Meter	9 Foot	Total Wt. (lbf)
A	0.60	0.29	62,700
A w/Shuttle	0.44	0.24	298,000
B	0.46	0.24	209,000
C	0.18	0.10	251,000
D	0.17	0.10	367,000
E	0.22	0.13	496,000

Note : Shuttle weight = 235,000 lbf

Table 4 : Gain Margins and Associated Frequencies for each Configuration

	9 Foot Bay Size			5 Meter Bay Size		
Configuration	X	Y	Z	X	Y	Z
B : Boom w/PV & US Modules	22 dB 0.24 Hz	35 dB 1.06 Hz	23 dB 0.24 Hz	30 dB 0.46 Hz	43 dB 1.44 Hz	33 dB 0.60 Hz
C : Boom w/PV, SD & US Mods	10 dB 0.10 Hz	23 dB 0.13 Hz	13 dB 0.10 Hz	21 dB 0.18 Hz	31 dB 0.24 Hz	25 dB 0.18 Hz
D : Boom w/PV, SD, US, & Inter. Modules	10 dB 0.10 Hz	21 dB 0.10 Hz	10 dB 0.10 Hz	21 dB 0.17 Hz	30 dB 0.17 Hz	22 dB 0.17 Hz
E : Reference Dual Keel	17 dB 0.13 Hz	18 dB 0.19 Hz	20 dB 0.14 Hz	26 dB 0.22 Hz	30 dB 0.33 Hz	29 dB 0.23 Hz

Notes :

1. Gain Margins correspond to a 0.01 Hz bandwidth and a 27.5% damping ratio.
2. This analysis was not performed for configuration A (Boom w/PV).
3. See appendices B, C, D, and E for the minimum gain margin Bode plots and associated mode shape plots.

5.0 Concluding Remarks

Vibration and attitude control analyses of several stages during buildup of an IOC space station were conducted. Both 9 foot and 5 meter truss bay sizes were investigated. All configurations analyzed were stable; however, the 5 meter truss bay size structure exhibited superior stability characteristics.

6.0 References

1. Program Definition and Program Requirements Document, JSC 30000, Section 3 : Space Station Systems Requirements Revision C, December 1986.

2. Kaszubowski, M. ; Raney, J. P. : "Analysis of The Effects of Firing Orbiter Primary Reaction Control System Jets with an Attached Truss Structure", NASA Technical Memorandum 89031, August, 1986.

3. Housner, Jerrold M. ; "Structural Dynamics Model and Response of the Deployable Reference Configuration Space Station", NASA Technical Memorandum 86386, May 1985.

4. Young, John W. ; Lallman, Frederick J. ; Cooper, Paul A. ; Giesy, Daniel P. : "Control/Structures Interaction Study of Two 300 KW Dual-Keel Space Station Concepts", NASA Technical Memorandum 87679, May, 1986.

APPENDIX A

Configuration A : Boom with Photo-voltaic

1. Table A-1 : Mass properties
2. Table A-2 : List of frequencies for Configuration A
3. Table A-3 : List of frequencies for Configuration A with shuttle attached
4. Selected mode shapes

Table A-1 : Mass Properties for Configuration A
(Boom with Photo-Voltaic)

Property	Value: Configuration A	Value: Configuration A w/shuttle Attached
Total Weight (lbf)	6.27 X 10**4	2.98 X 10**5
X c.g. (in)	-22.0	-5.0
Y c.g. (in)	120.0	1910.0
Z c.g. (in)	-9.0	-2.0
Ixx (in-lbf-s**2)	1.25 X 10**11	3.84 X 10**11
Ixy (in-lbf-s**2)	-1.73 X 10**9	7.84 X 10**9
Iyy (in-lbf-s**2)	3.47 X 10**11	3.85 X 10**11
Iyz (in-lbf-s**2)	2.33 X 10**9	2.43 X 10**9
Ixz (in-lbf-s**2)	-5.93 X 10**9	3.80 X 10**9
Izz (in-lbf-s**2)	1.24 X 10**11	4.13 X 10**11

Notes : 1. C.G. measured from middle of center bay
2. Inertias taken about C.G.

TABLE A-2: CONFIGURATION A

<u>BOOM W/PV</u>

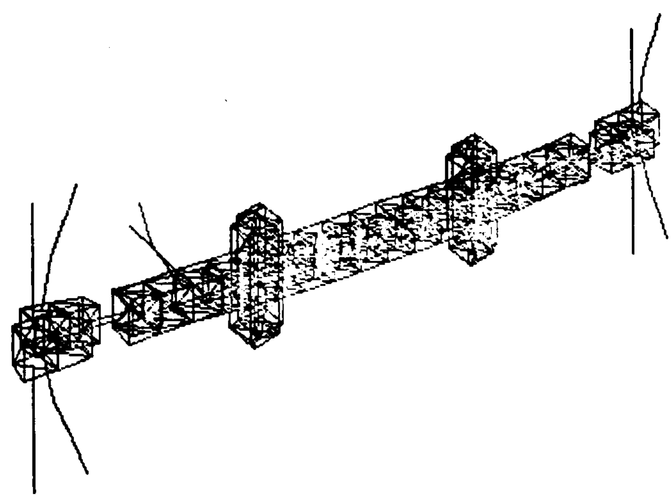
	9 FOOT		5 METER	
MODE DESCRIPTION	MODE NUMBER(S)	FREQ. (HZ)	MODE NUMBER(S)	FREQ. (HZ)
RIGID BODY	1-6	0.0	1-6	0.0
APPENDAGE MODES	7-8 10,12-15	0.22-0.23 0.32-0.36	7-16 19-20	0.22-0.40 1.31-1.34
COUPLED BENDING (+X,-Z)	9*	0.29	18	0.73
COUPLED BENDING (+X,+Z)	11	0.33	17*	0.601
BENDING IN Z ONLY	16	0.38	-	-
BENDING IN X ONLY	18	0.43	-	-
TORSION ABOUT Y	17*	0.39	22*	1.551
2ND COUPLED BEND. (+X, -Z)	19	0.85	21	1.493
2ND COUPLED BEND. (+X,+Z)	21	0.98	23	1.70

*SEE MODE SHAPE PLOTS.

Configuration A

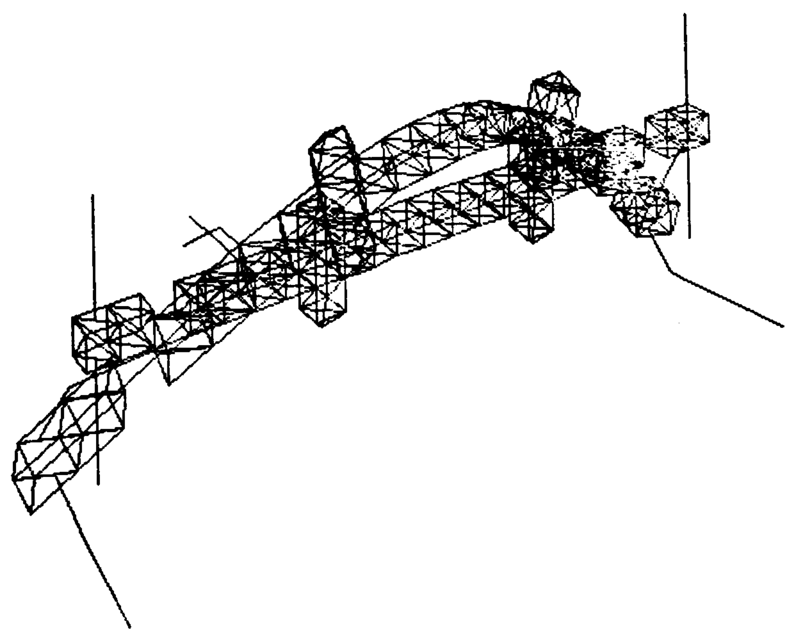
9 foot bay size

mode # 9, freq. = 0.29 Hz



Configuration A

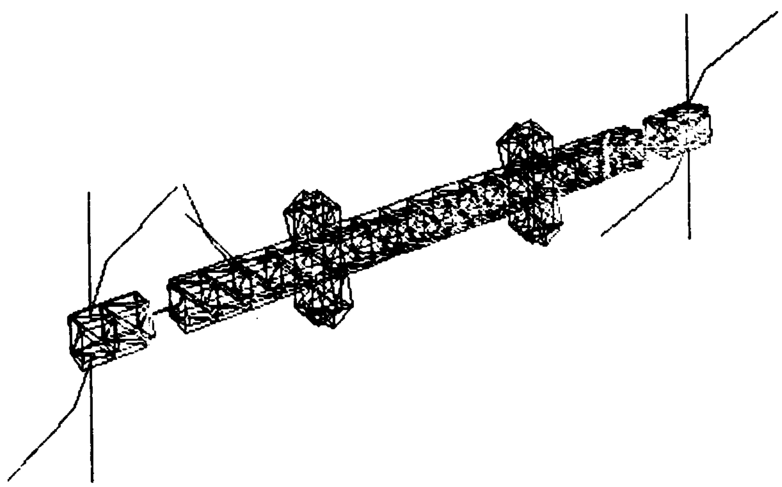
5 meter bay size
mode # 17, freq. = 0.60 Hz



Configuration A

9 foot bay size

mode # 17, freq. = 0.39 Hz



Configuration A

5 meter bay size

mode # 22, freq. = 1.55 Hz

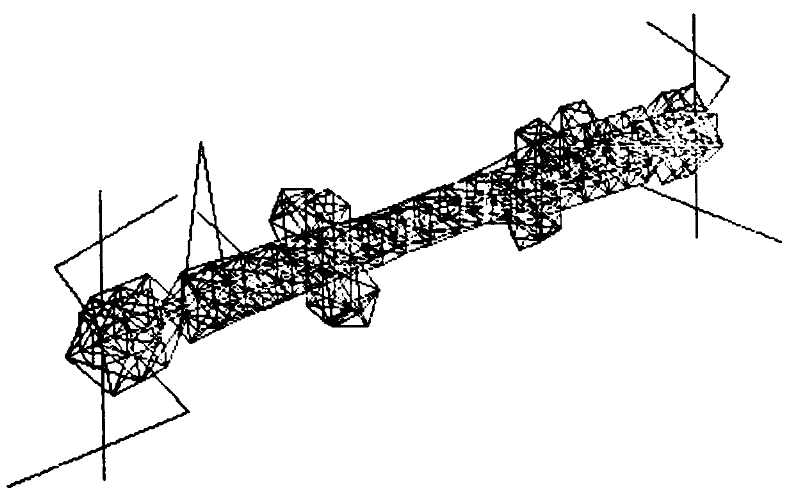


TABLE A-3: CONFIGURATION A

BOOM W/PV, W/SHUTTLE

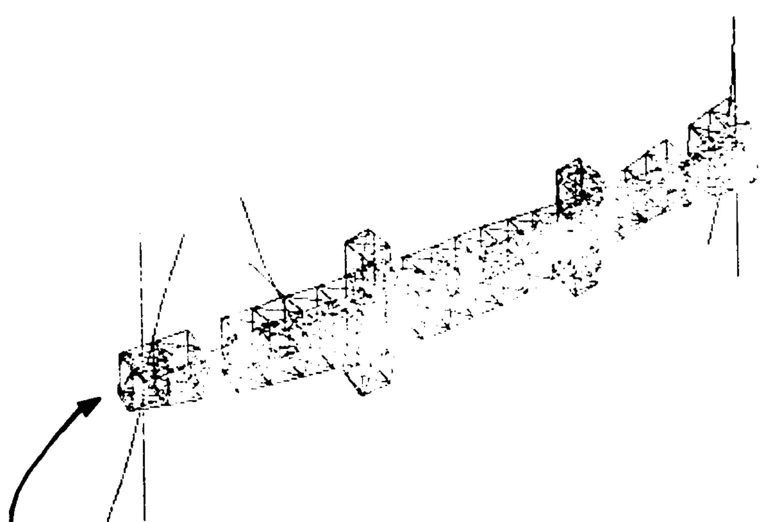
	9 FOOT		5 METER	
MODE DESCRIPTION	MODE NUMBER(S)	FREQ. (HZ)	MODE NUMBER(S)	FREQ. (HZ)
RIGID BODY	1-6	0.0	1-6	0.0
APPENDAGE MODES	7-9 12-18	0.17-0.21 0.35-0.37	7-17 22-23	0.21-0.37 1.33-1.33
1ST BENDING (Z)	10*	0.24	18*	0.44
1ST BENDING (X)	11	0.28	20	0.75
TORSION ABOUT Y	19*	0.43	19*	0.55
2ND BENDING (X)	21	0.65	21	1.07
2ND TORSION ABOUT Y	22	0.92	24	1.63
2ND BENDING (Z)	24	1.17	26	1.98
COUPLED BENDING AND TORSION	23	0.99	25	1.70

*SEE MODE SHAPE PLOTS.

Configuration A w/shuttle

9 foot bay size

mode # 10, freq. = 0.24 Hz

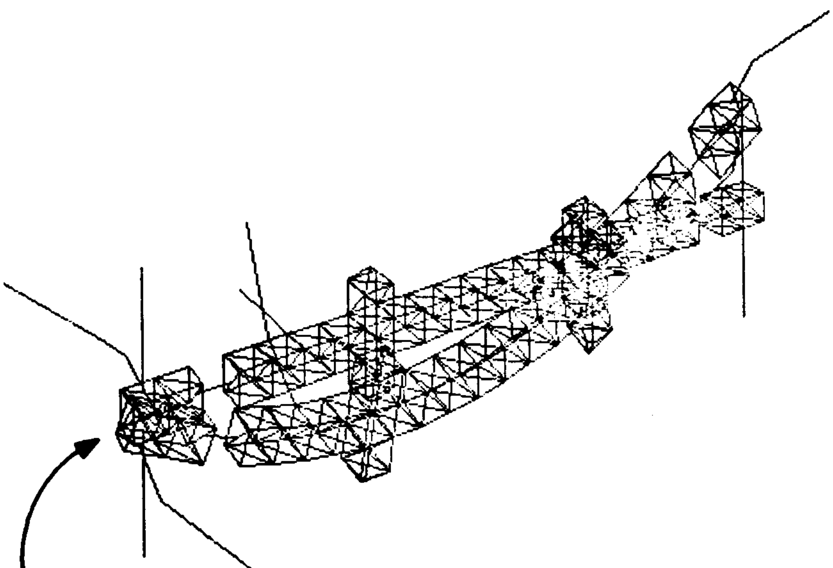


Shuttle attachment point

Configuration A w/shuttle

5 meter bay size

mode # 18, freq. = 0.44 Hz

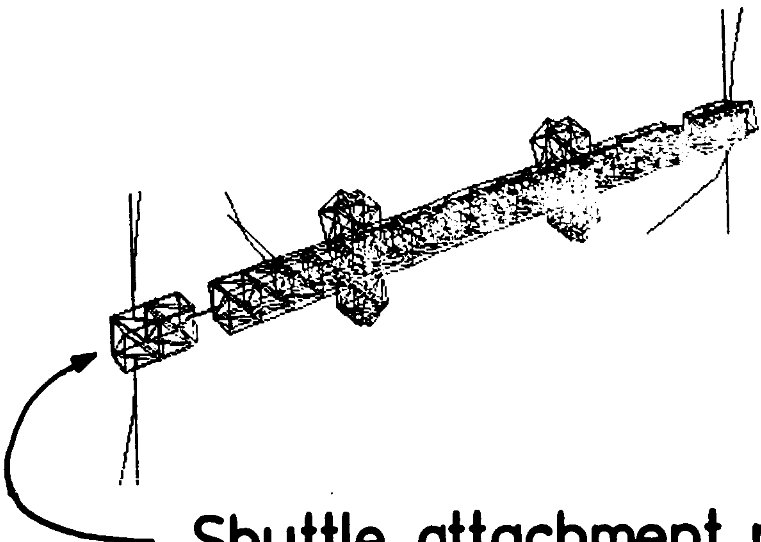


Shuttle attachment point

Configuration A w/shuttle

9 foot bay size

mode # 19, freq. = 0.43 Hz

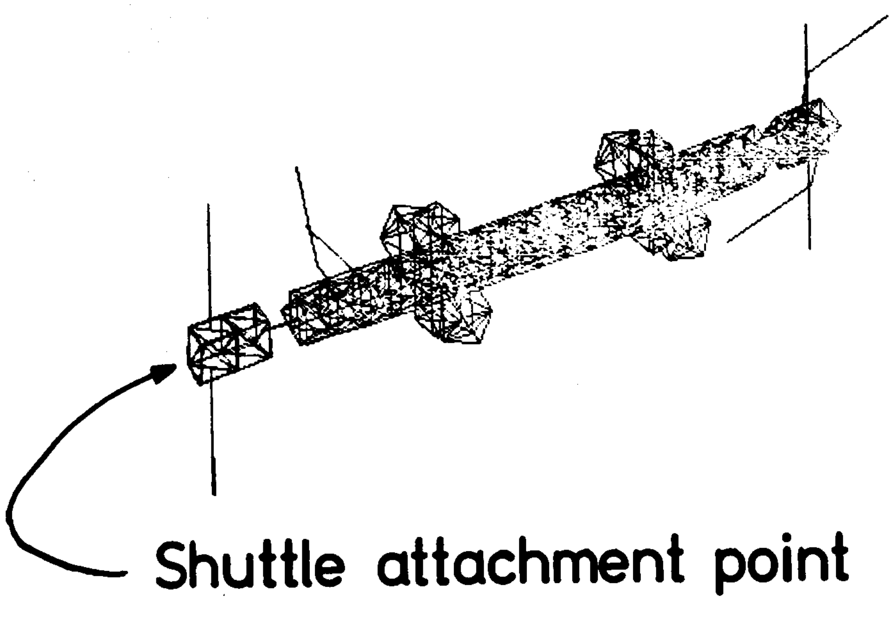


Shuttle attachment point

Configuration A w/shuttle

5 meter bay size

mode # 19, freq. = 0.55 Hz



APPENDIX B

Configuration B : Boom with Photo-voltaic & US Modules

1. Table B-1 : Mass properties
2. Table B-2 : List of frequencies for Configuration B
3. Figure B-1 : Minimum gain margin Bode plots
4. Selected mode shapes

Table B-1 : Mass Properties for Configuration B
(Boom with PV and US Modules)

Property	Value
Total Weight (lbf)	2.09 X 10**5
X c.g. (in)	20.0
Y c.g. (in)	-66.0
Z c.g. (in)	-172.0
Ixx (in-lbf-s**2)	1.36 X 10**11
Ixy (in-lbf-s**2)	-2.66 X 10**9
Iyy (in-lbf-s**2)	1.46 X 10**11
Iyz (in-lbf-s**2)	-1.28 X 10**9
Ixz (in-lbf-s**2)	2.04 X 10**9
Izz (in-lbf-s**2)	1.40 X 10**11

Notes : 1. C.G. measured from middle of center bay
2. Inertias taken about C.G.

TABLE B-2: CONFIGURATION B

BOOM W/PV AND U.S. MODULES

	9 FOOT		5 METER	
MODE DESCRIPTION	MODE NUMBER(S)	FREQ. (HZ)	MODE NUMBER(S)	FREQ. (HZ)
RIGID BODY	1-6	0.0	1-6	0.0
APPENDAGE MODES	7-8 11-18	0.21-0.22 0.32-0.63	7-16 20-21	0.21 -0.36 1.30 -1.33
COUPLED BENDING (+X,-Z)*	9*	0.30	18	0.46
COUPLED BENDING (+X,+Z)	10	0.24	17*	0.60
2ND COUPLED BEND. (+X, -Z)	19	0.63	19	1.06
2ND COUPLED BEND. (+X, +Z)	20	0.83	22	1.44
TORSION ABOUT Y, (PORT)*	21*	1.06	23*	1.76
TORSION ABOUT Y, (STARBOARD)	22	1.23	24	1.84

* SEE MODE SHAPE PLOTS.

Figure B−1a : Configuration B, 9 foot

X−axis Bode Plot

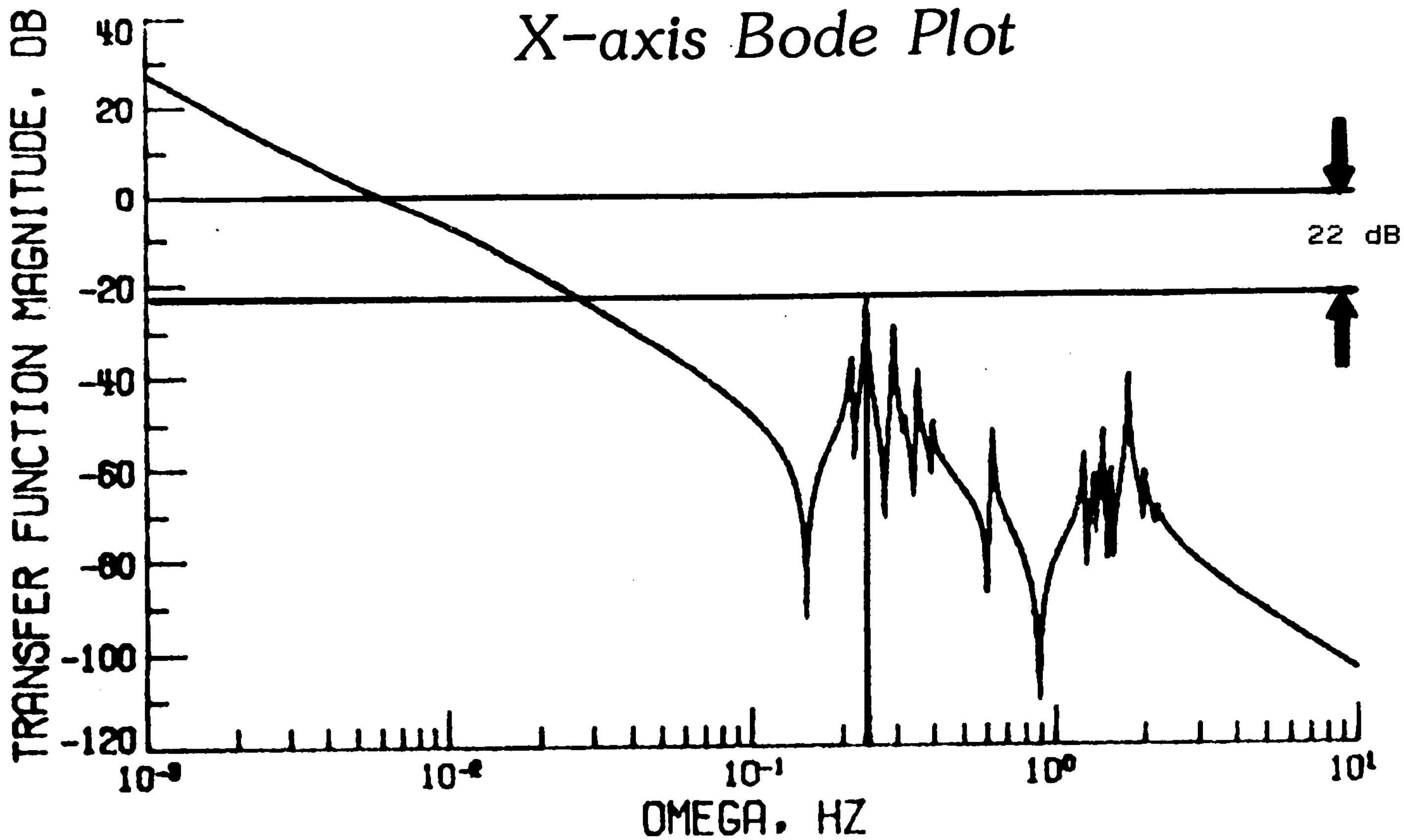
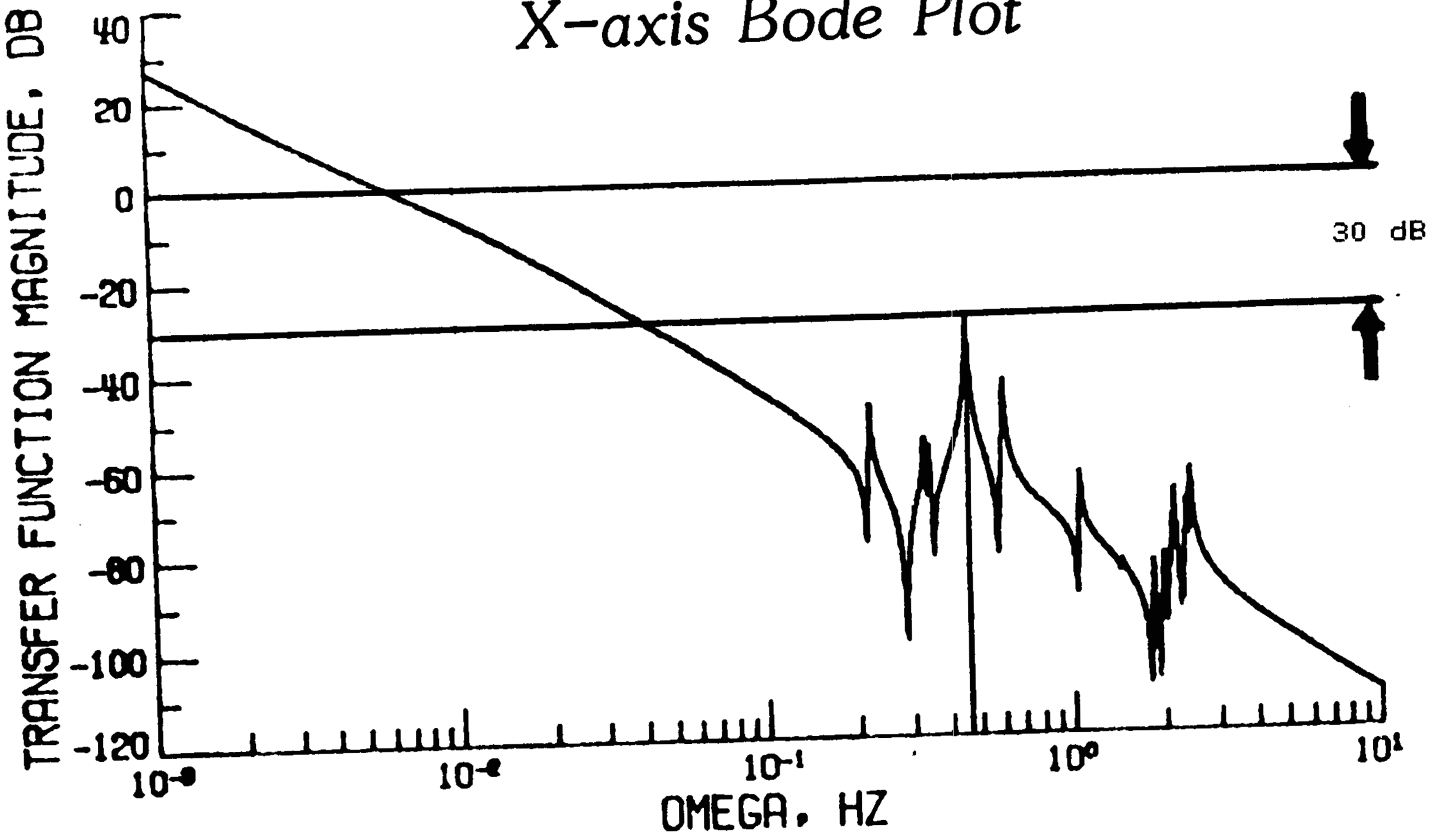


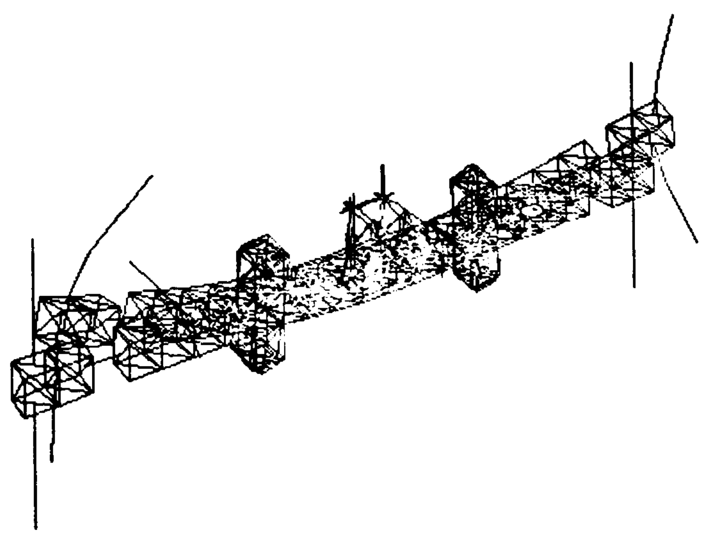
Figure B-1b : Configuration B, 5 meter X-axis Bode Plot



Configuration B

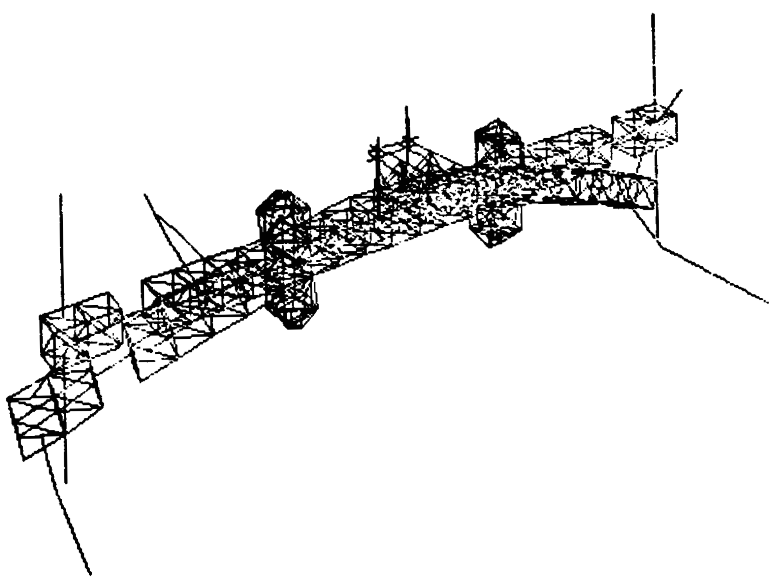
9 foot bay size

mode # 9, freq. = 0.24 Hz



Configuration B

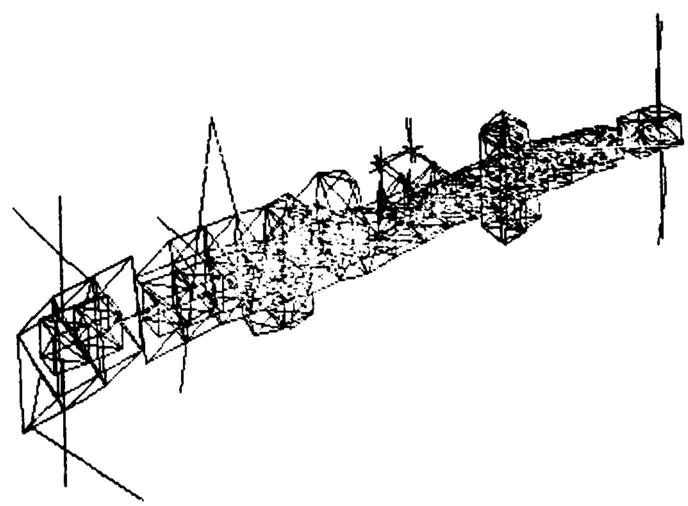
5 meter bay size
mode # 17, freq. = 0.46 Hz



Configuration B

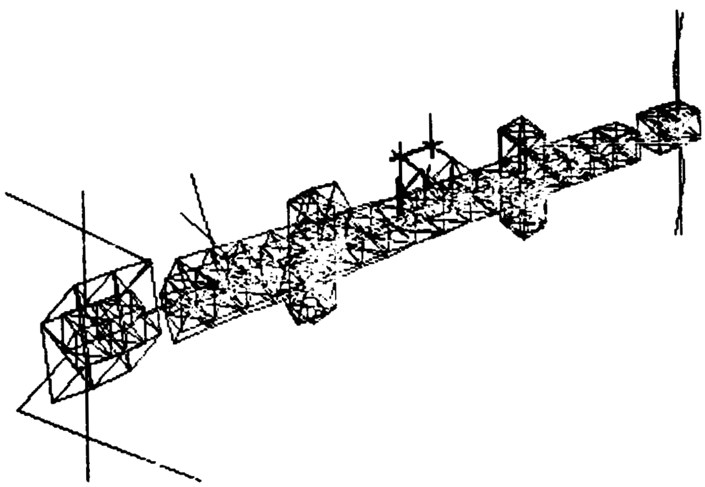
9 foot bay size

mode # 21, freq. = 1.06 Hz



Configuration B

5 meter bay size
mode # 23, freq. = 1.76 Hz



APPENDIX C

Configuration C : Boom with Photo-voltaic, Solar Dynamic & US Modules

1. Table C-1 : Mass properties

2. Table C-2 : List of frequencies for Configuration C

3. Figure C-1 : Minimum gain margin Bode plots

4. Selected mode shapes

Table C-1 : Mass Properties for Configuration C
(Boom with PV, SD and US Modules)

Property	Value
Total Weight (lbf)	2.51 X 10**5
X c.g. (in)	15.0
Y c.g. (in)	-72.0
Z c.g. (in)	-123.0
Ixx (in-lbf-s**2)	4.82 X 10**11
Ixy (in-lbf-s**2)	-5.63 X 10**9
Iyy (in-lbf-s**2)	1.95 X 10**11
Iyz (in-lbf-s**2)	-1.40 X 10**9
Ixz (in-lbf-s**2)	2.80 X 10**9
Izz (in-lbf-s**2)	4.81 X 10**11

Notes : 1. C.G. measured from middle of center bay
2. Inertias taken about C.G.

TABLE C-2: CONFIGURATION C

BOOM W/PV, SD, U.S. MODULES

	9 FOOT		5 METER	
MODE DESCRIPTION	MODE NUMBER(S)	FREQ. (HZ)	MODE NUMBER(S)	FREQ. (HZ)
RIGID BODY	1-6	0.0	1-6	0.0
APPENDAGE MODES	9-22	0.21-0.51	9-21	0.21-0.50
COUPLED BENDING (+X,-Z)	7*	0.10	7*	0.18
COUPLED BENDING (+X,+Z)	8	0.13	8	0.20
2ND BENDING (+X,+Z)	23	0.51	22	0.57
PORT AND STARBOARD TORSION	25*	0.69	23*	0.81
2ND BENDING (+X,-Z)	24	0.57	24	0.95
COUPLED TORSION AND BENDING	27	0.88	25	1.06

*SEE MODE SHAPE PLOTS.

Figure C–1a : Configuration C, 9 foot

X–axis Bode Plot

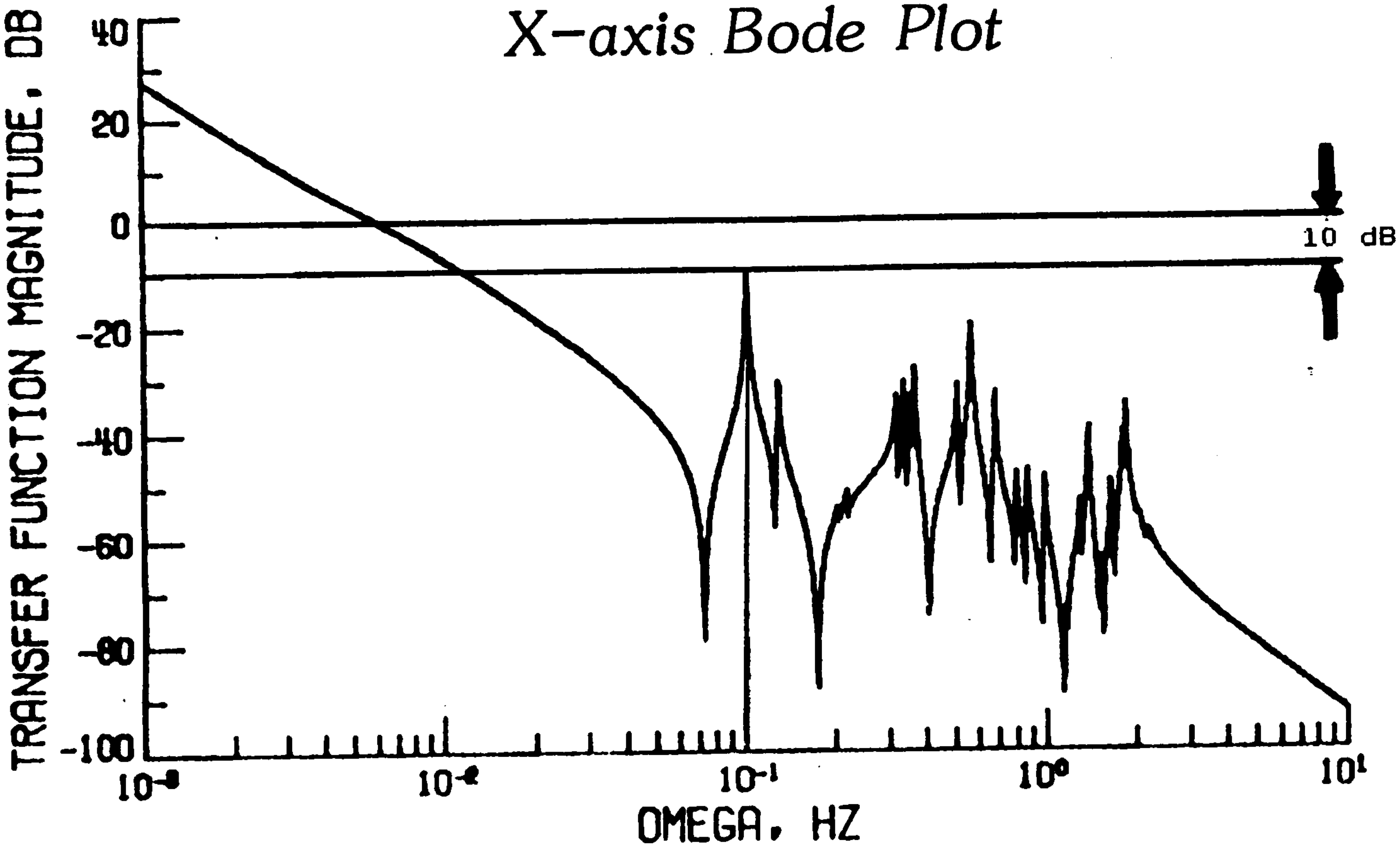
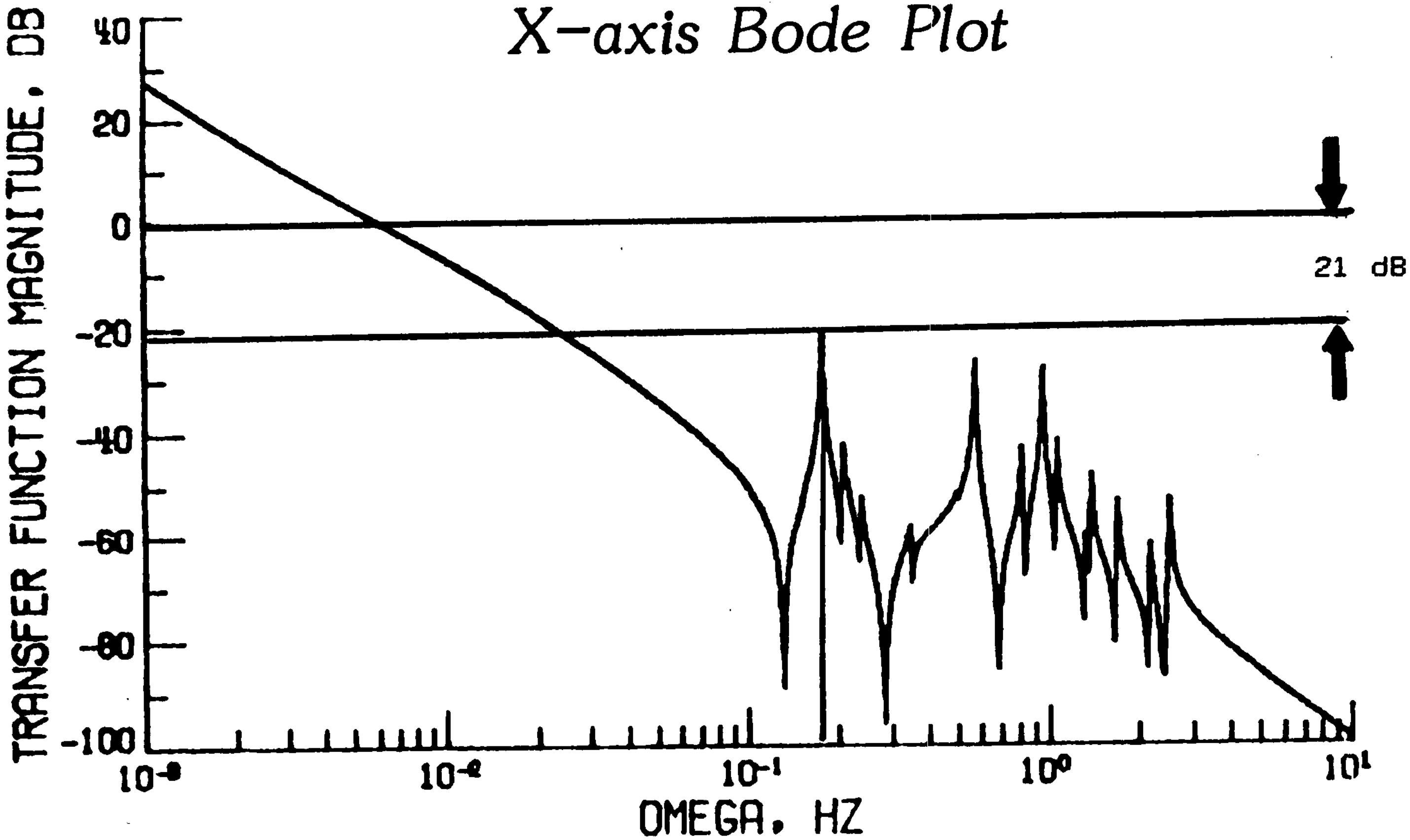


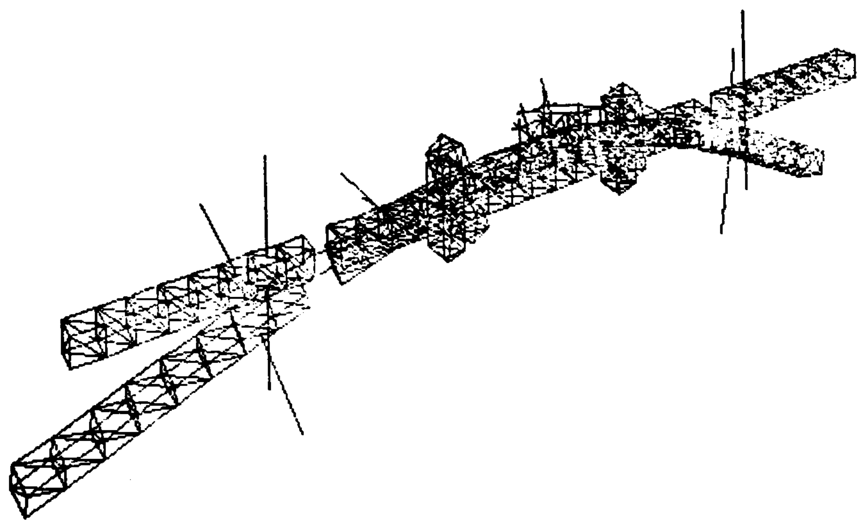
Figure C−1b : Configuration C, 5 meter
X−axis Bode Plot



Configuration C

9 foot bay size

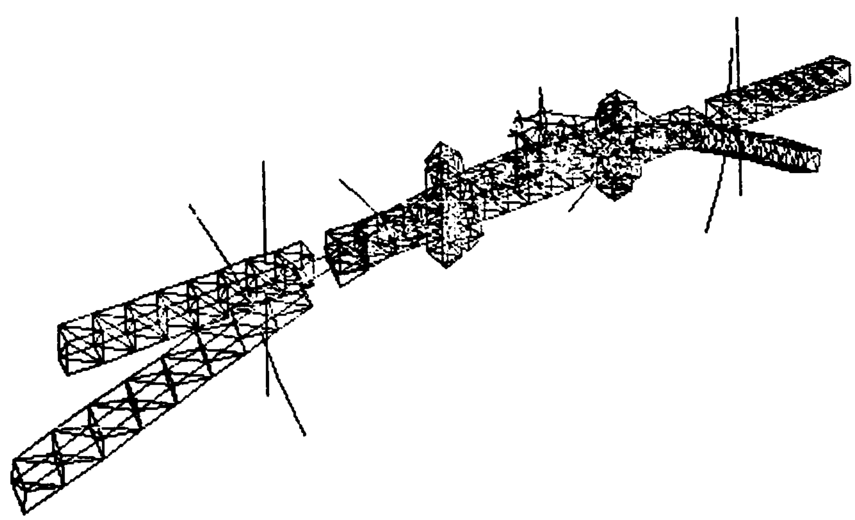
mode # 7, freq. = 0.10 Hz



Configuration C

5 meter bay size

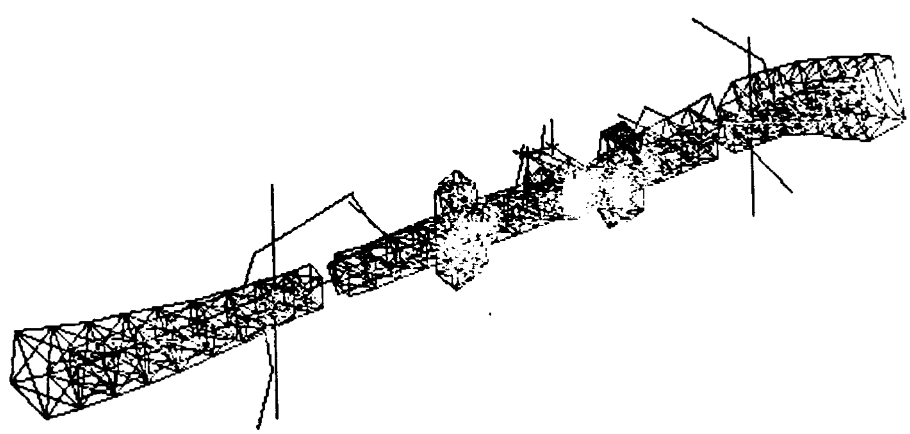
mode # 7, freq. = 0.18 Hz



Configuration C

9 foot bay size

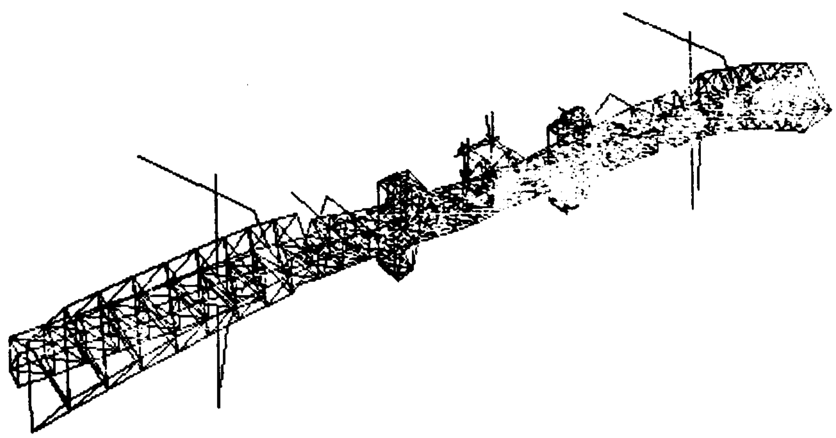
mode # 25, freq. = 0.69 Hz



Configuration C

5 meter bay size

mode # 23, freq. = 0.82 Hz



APPENDIX D

Configuration D : Boom with Photo-voltaic, Solar Dynamic, US and International Modules

1. Table D-1 : Mass properties
2. Table D-2 : List of frequencies for Configuration D
3. Figure D-1 : Minimum gain margin Bode plots
4. Selected mode shapes

Table D-1 : Mass Properties for Configuration D
(Boom w/PV, SD, US and Inter. Modules)

Property	Value
Total Weight (lbf)	3.67 X 10**5
X c.g. (in)	-18.0
Y c.g. (in)	-91.0
Z c.g. (in)	-173.0
Ixx (in-lbf-s**2)	4.86 X 10**11
Ixy (in-lbf-s**2)	3.56 X 10**9
Iyy (in-lbf-s**2)	3.73 X 10**11
Iyz (in-lbf-s**2)	5.92 X 10**9
Ixz (in-lbf-s**2)	3.57 X 10**9
Izz (in-lbf-s**2)	5.19 X 10**11

Notes : 1. C.G. measured from middle of center bay
2. Inertias taken about C.G.

TABLE D-2: CONFIGURATION D

BOOM W/PV, SD, U.S. AND INT. MODULES

	9 FOOT		5 METER	
MODE DESCRIPTION	MODE NUMBER(S)	FREQ. (HZ)	MODE NUMBER(S)	FREQ. (HZ)
RIGID BODY	1-6	0.0	1-6	0.0
APPENDAGE MODES	9-12 14-21	0.21-0.21 0.32-0.35	9-20 23-24	0.21-0.35 0.77-0.86
COUPLED BENDING (+X,-Z)	7*	0.10	7*	0.17
COUPLED BENDING (+X,+Z)	8	0.12	8	0.20
TORSION ABOUT Y	13*	0.24	21*	0.40
2ND COUPLED BENDING (+X, -Z)	22	0.36	22	0.56
2ND COUPLED BENDING (+X,+Z)	24	0.57	25	0.95

* SEE MODE SHAPE PLOTS.

Figure D–1a : Configuration D, 9 foot

X–axis Bode Plot

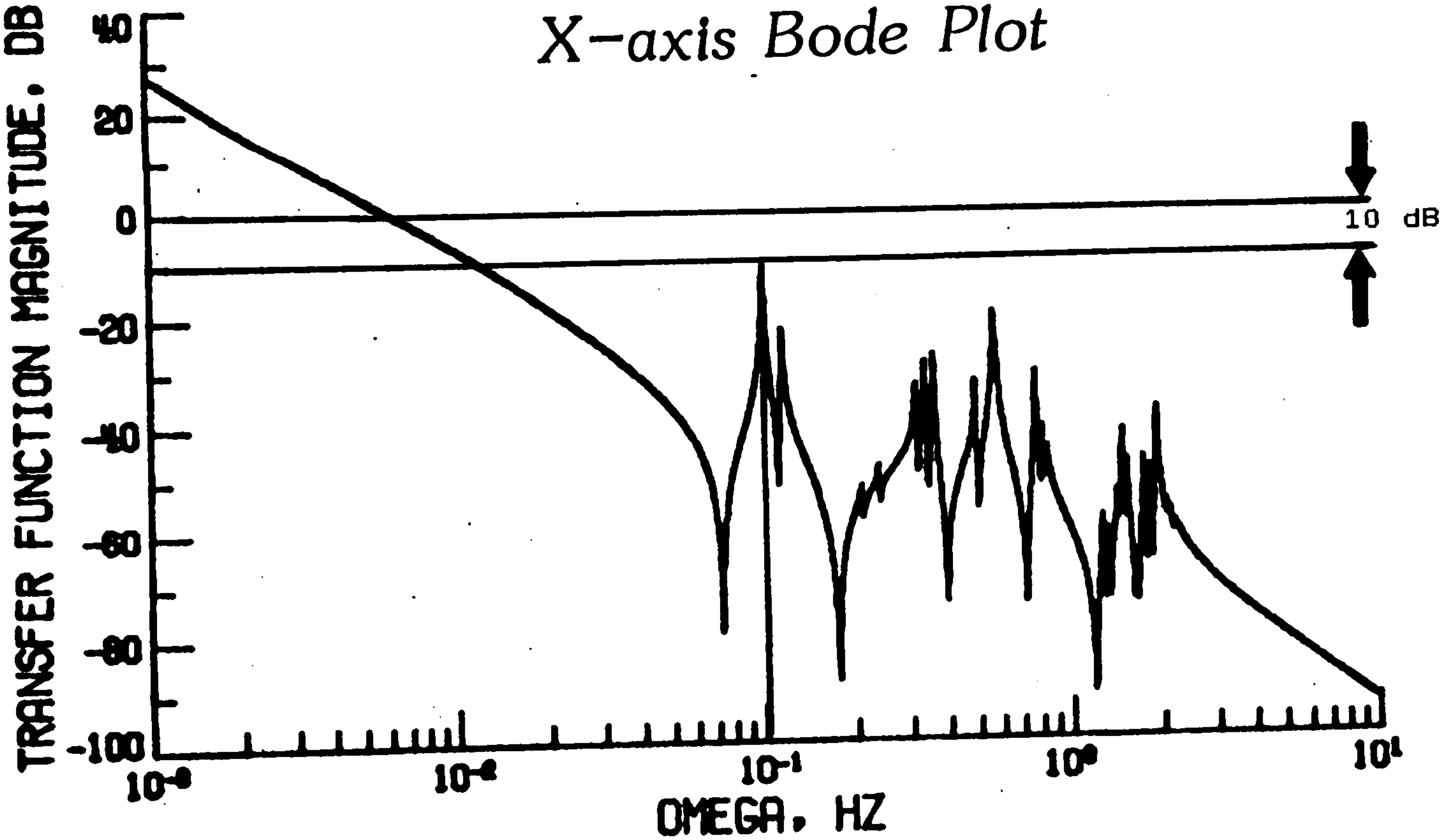
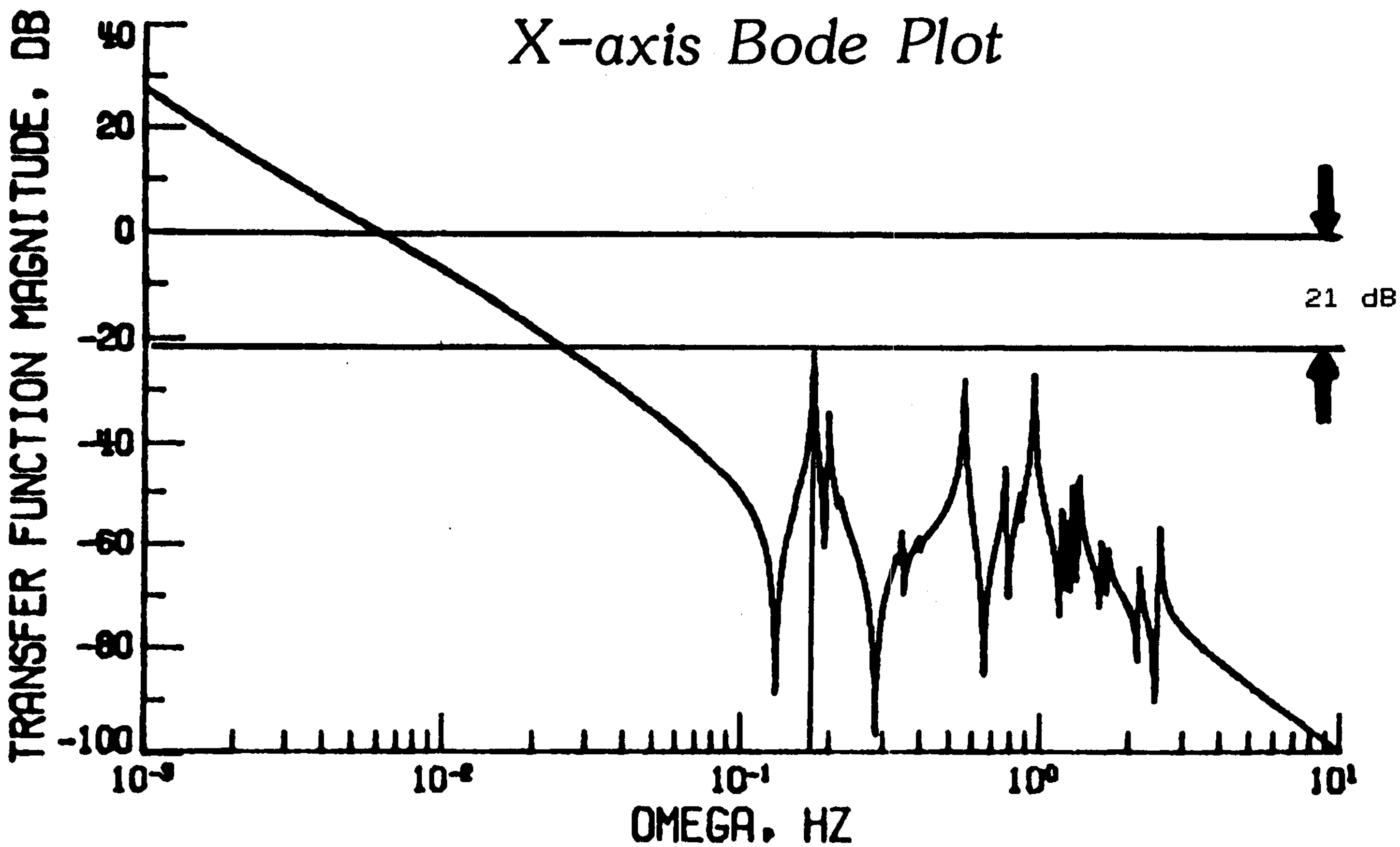


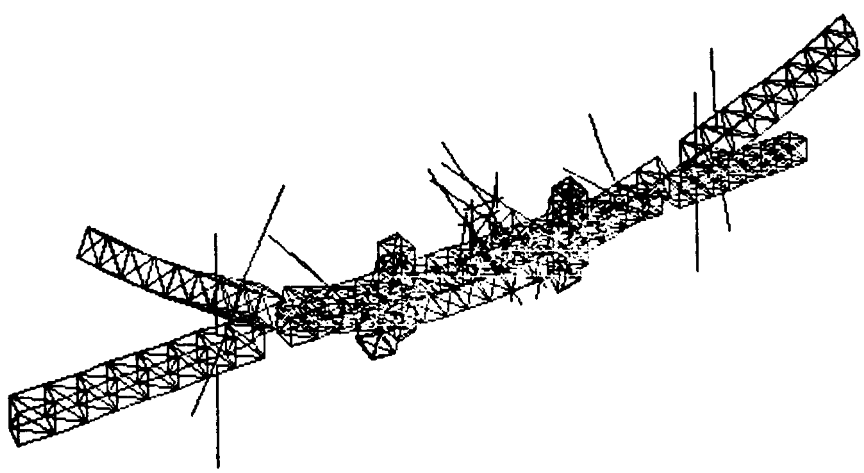
Figure D–1b : Configuration D, 5 meter

X–axis Bode Plot



Configuration D

9 foot bay size
mode # 7, freq. = 0.10 Hz



Configuration D

5 meter bay size
mode # 7, freq. = 0.17 Hz

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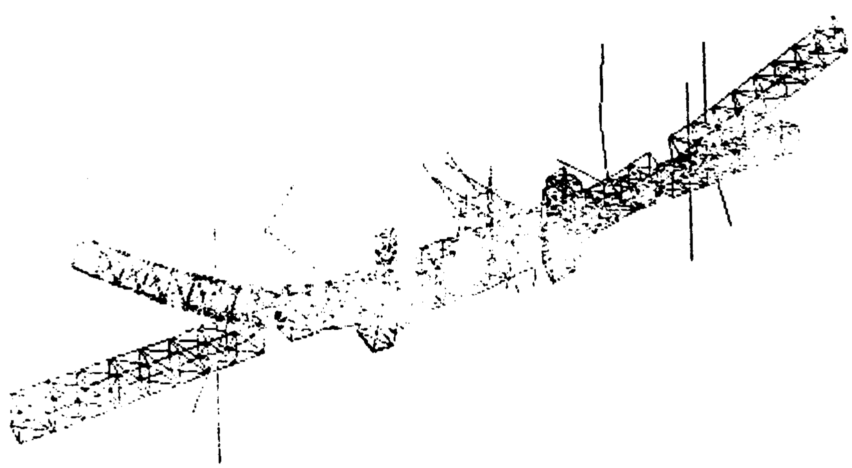
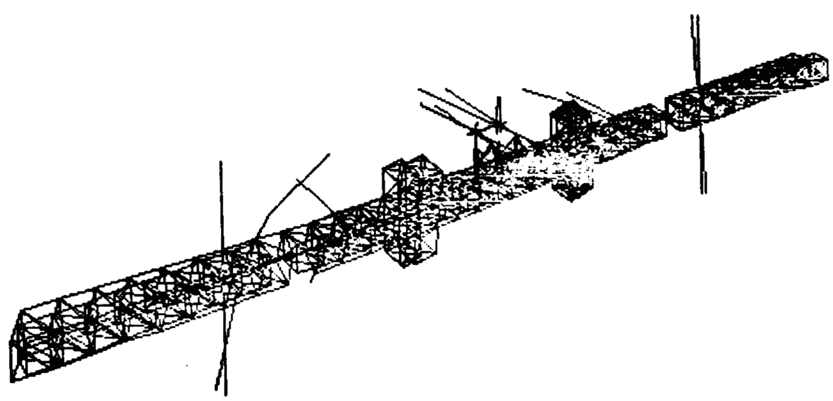


Configuration D

9 foot bay size

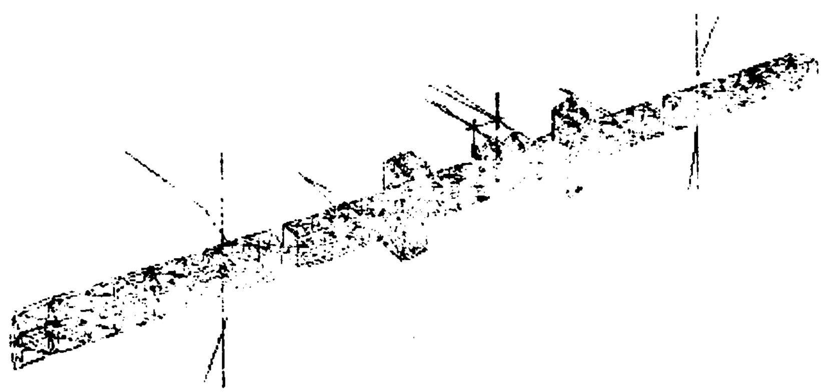
mode # 13, freq. = 0.24 Hz



Configuration D

5 meter bay size

mode # 21, freq. = 0.40 Hz



APPENDIX E

Configuration E : Reference Dual Keel

1. Table E-1 : Mass properties
2. Table E-2 : List of frequencies for Configuration E
3. Figure E-1 : Minimum gain margin Bode plots
4. Selected mode shapes

Table E-1 : Mass Properties for Configuration E
(Reference Dual Keel)

Property	Value
Total Weight (lbf)	4.96 X 10**5
X c.g. (in)	-141.0
Y c.g. (in)	-109.0
Z c.g. (in)	-180.0
Ixx (in-lbf-s**2)	8.14 X 10**11
Ixy (in-lbf-s**2)	3.33 X 10**9
Iyy (in-lbf-s**2)	3.87 X 10**11
Iyz (in-lbf-s**2)	8.71 X 10**9
Ixz (in-lbf-s**2)	5.52 X 10**9
Izz (in-lbf-s**2)	5.30 X 10**11

Notes : 1. C.G. measured from middle of center bay
2. Inertias taken about C.G.

TABLE E-2: CONFIGURATION E

REFERENCE DUAL KEEL

	9 FOOT		5 METER	
MODE DESCRIPTION	MODE NUMBER(S)	FREQ. (HZ)	MODE NUMBER(S)	FREQ. (HZ)
RIGID BODY	1-6	0.0	1-6	0.0
APPENDAGE MODES	13-21	0.28-0.29	9-17 22-34	0.28-0.29 0.43-0.51
TRANS. BOOM BEND. & TORSION	7*	0.13	7*	0.22
TRANS. BOOM BEND. & TORSION	8*	0.14	8*	0.23
BOOM BEND., UPPER KEEL BEND.	9	0.16	-	-
BOOM BEND., LOWER KEEL BEND.	-	-	18	0.31
UPPER AND LOWER KEEL BEND.	10,11	0.19,0.21	19,20	0.33,0.36
KEEL TWISTING	12*	0.22	21*	0.39
PORT KEEL BENDING	22	0.34	35	0.58

*SEE MODE SHAPE PLOTS.

Figure E-1a : Configuration E, 9 foot

X-axis Bode Plot

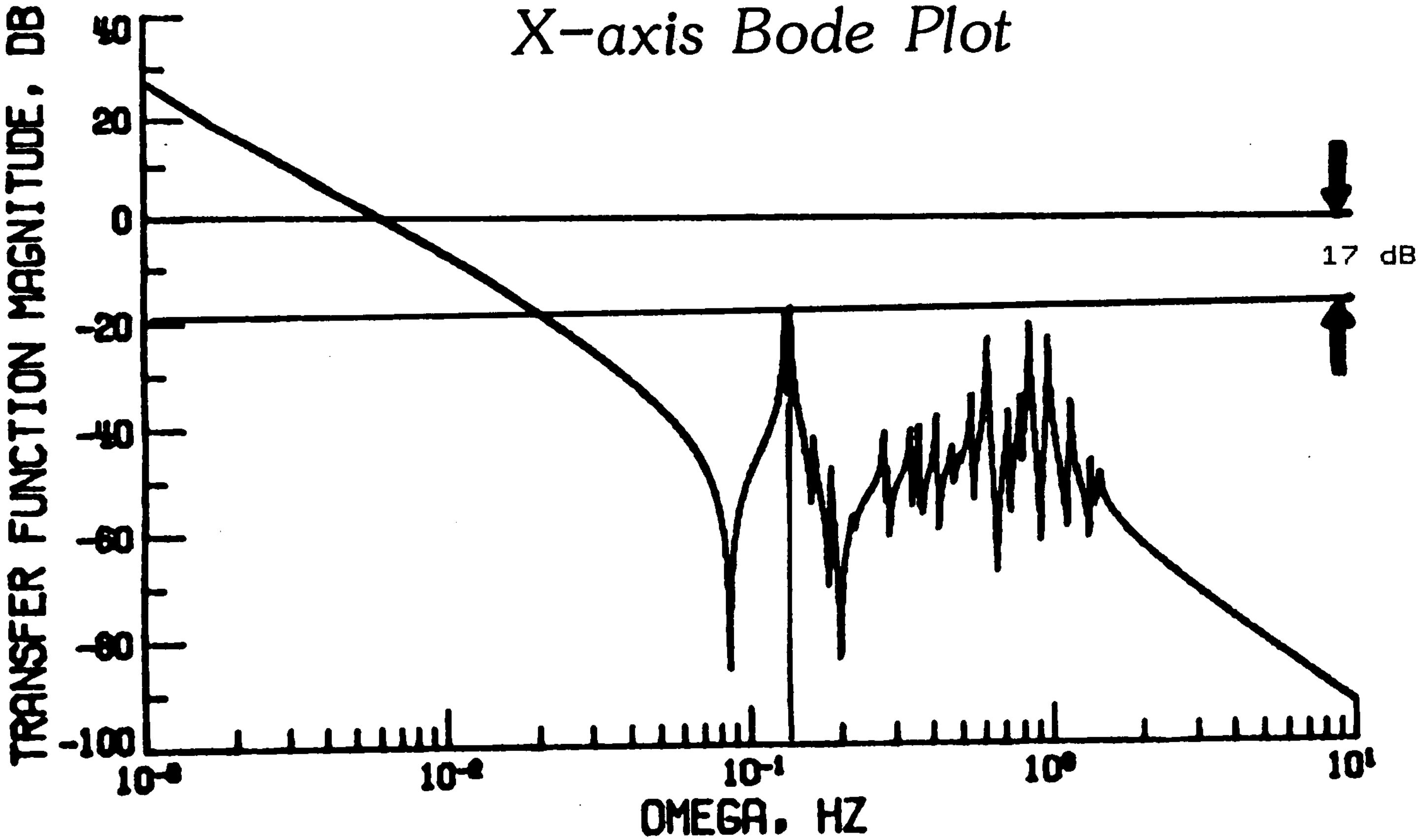
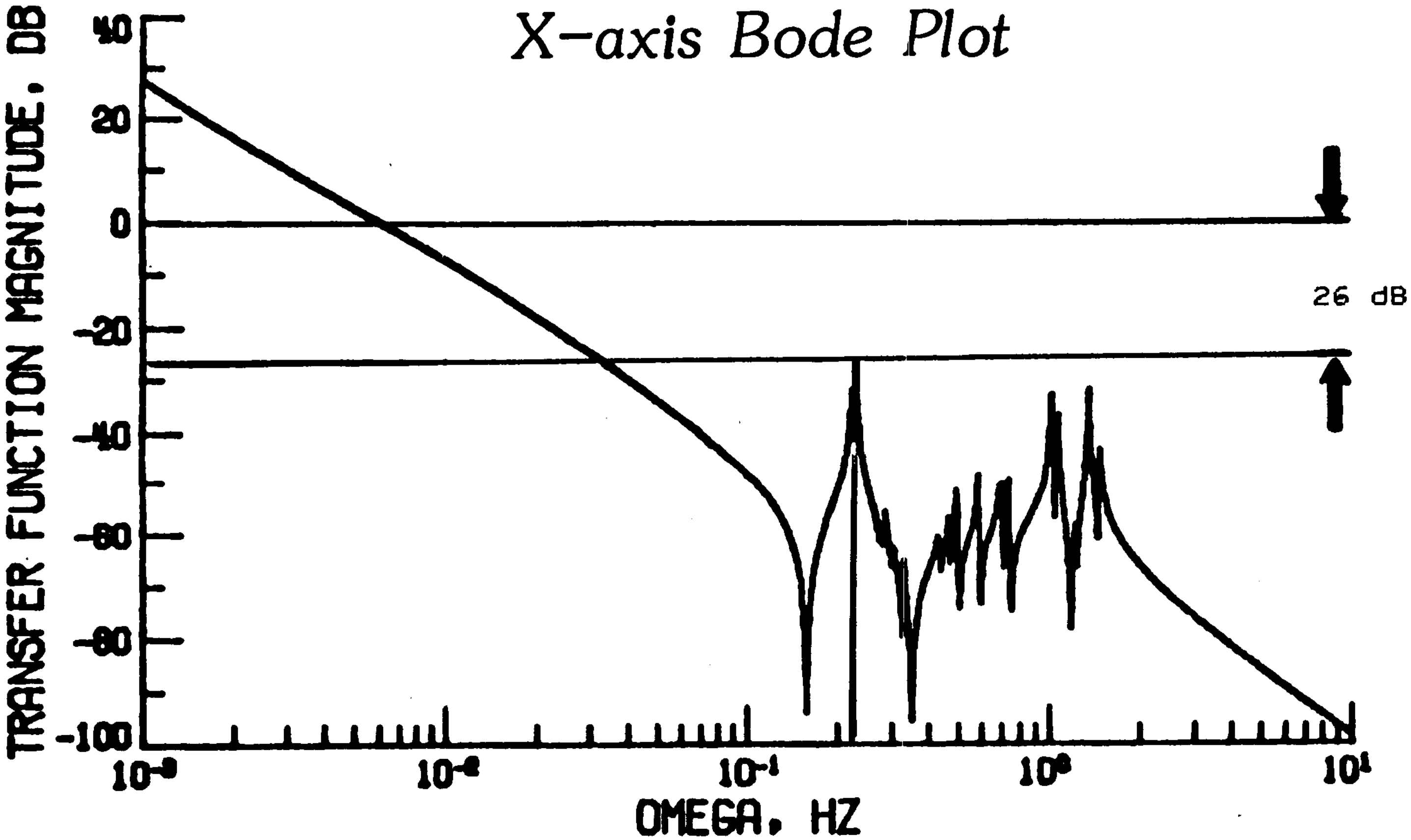


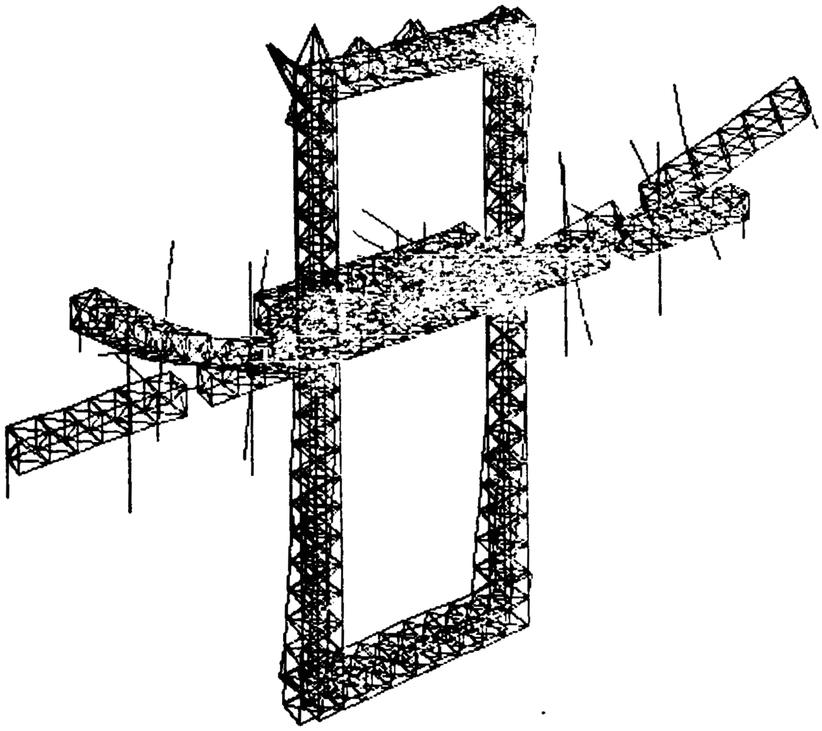
Figure E–1b : Configuration E, 5 meter

X–axis Bode Plot



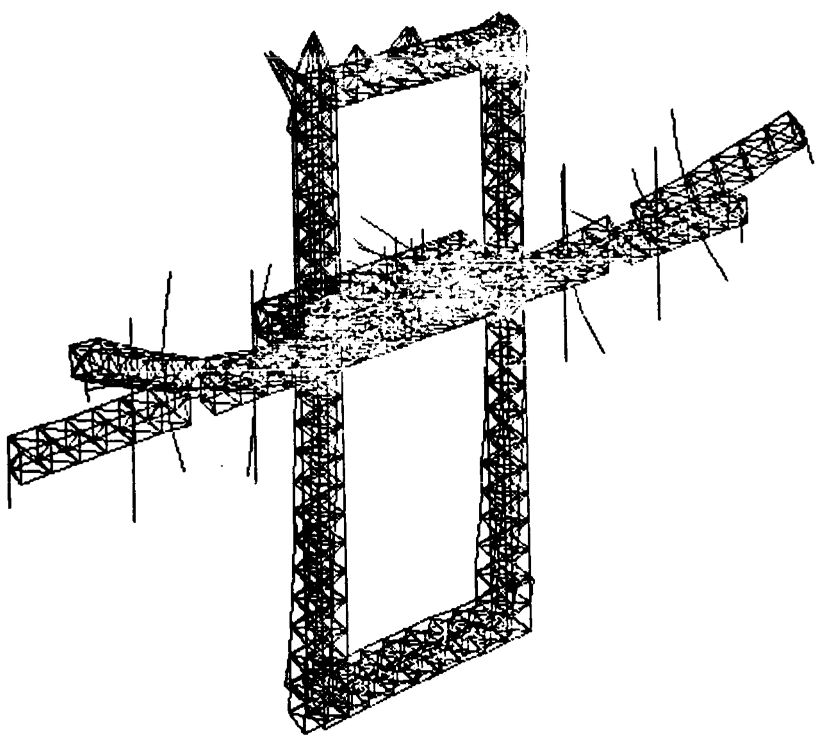
Configuration E

9 foot bay size
mode # 7, freq. = 0.13 Hz



Configuration E

5 meter bay size
mode # 7, freq. = 0.22 Hz



Configuration E

9 foot bay size

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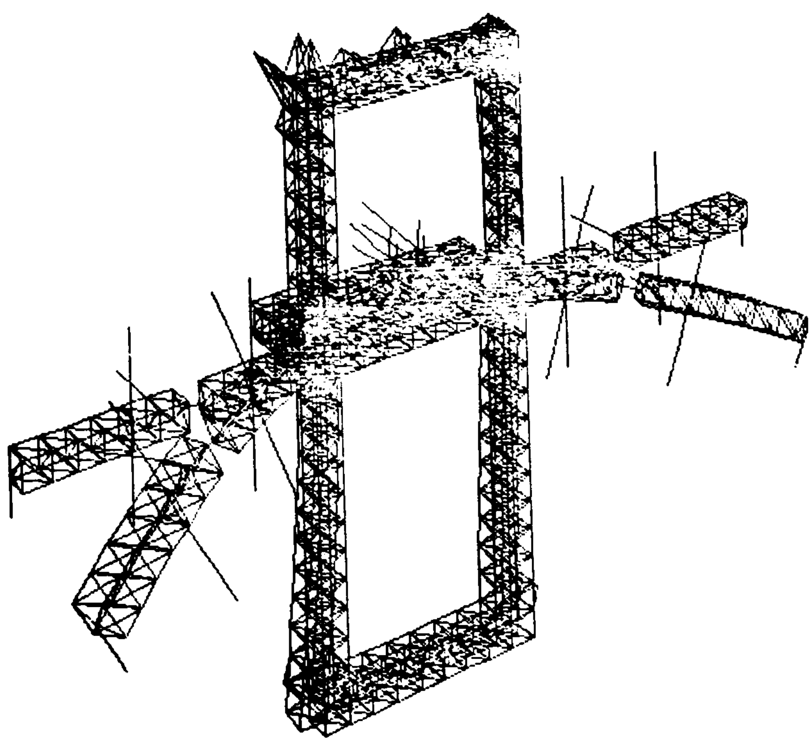
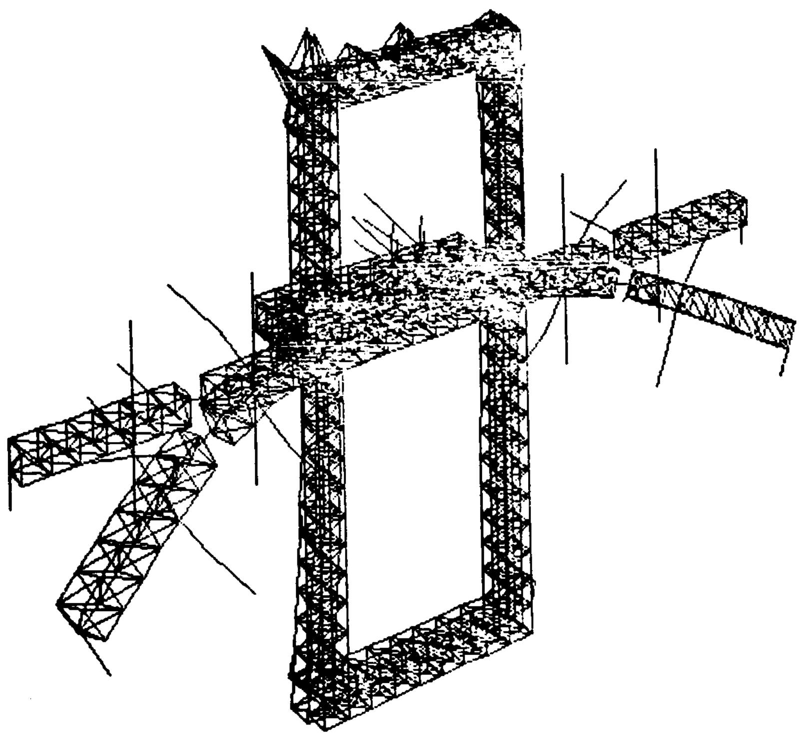


Configuration E

5 meter bay size

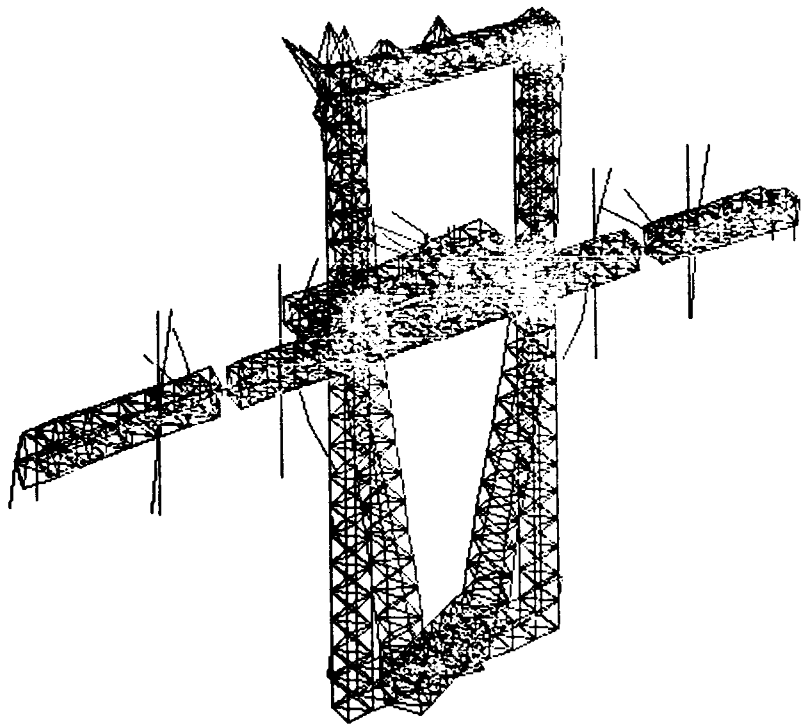
mode # 8, freq. = 0.23 Hz



Configuration E

9 foot bay size

mode # 12, freq. = 0.22 Hz



Configuration E
5 meter bay size
mode # 21, freq. = 0.39 Hz

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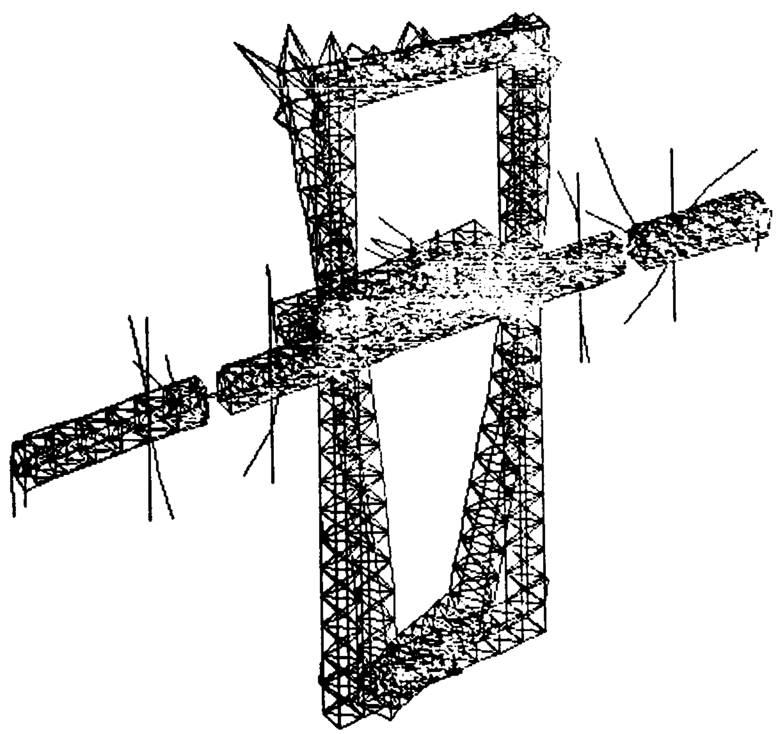

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16. Abstract

A study was performed to determine the vibration and attitude control characteristics of critical Space Station configurations featuring early manned capability during buildup from initial user support through the operations capability reference station. Five configurations were selected and were examined thus determining the changes that are likely to occur in the characteristics of the system as the station progresses from a single boom structure to a mature, dual keel, operations capability reference station. Both 9 foot and 5 meter truss bay sizes were investigated. All configurations analyzed were stable; however, the 5 meter truss bay size structure exhibited superior stability characteristics.

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